THE INTERNATIONAL COLLOQUIUM ON STABILITY AND DUCTILITY OF STEEL STRUCTURES

11-13 September 2019,
Prague, Czech Republic

BOOK OF ABSTRACTS

Editors
František Wald & Michal Jandera
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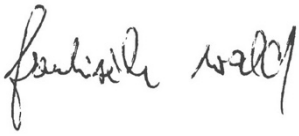
Foreword

The series of International Colloquia on Stability and Ductility of Steel Structures have been supported by the Structural Stability Research Council (SSRC) for more than forty years and its objective is to present the progress in theoretical, numerical and experimental research in the field of stability and ductility of steel and steel-concrete composite structures. Special emphasis is laid on new concepts and procedures concerning the analysis and design of steel structures and on the background, development and application of rules and recommendations either appearing in recently published Codes or Specifications or about to be included in their upcoming versions. This International Colloquium series started in 1972 in Paris and its subsequent editions took place in different cities with the last five being held in: Timisoara, Romania (1999), Budapest, Hungary (2002), Lisbon, Portugal (2006), Rio de Janeiro, Brazil (2010) and Timisoara, Romania (2016).

The 2019 edition of SDSS is organized by the Czech Technical University in Prague. The university held the second edition of the Eurosteel conference in 1999 and the first three editions of Applications of Structural Fire Engineering (ASFE) conference (2009, 2011 and 2013).

František Wald, Chairman & **Michal Jandera,** Scientific Secretary



SDSS 2019 Prague 11-13 September

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Programme Overview

Wednesday 11/9			
07:30 - 08:30	**Registration** Location: Atrium		
08:30 - 09:00	**Opening Session** Location: B286		
09:00 - 10:00	**K1: Keynote Lectures** Location: B286		
10:00 - 10:30	**Coffee Break** Location: Atrium		
10:30 - 12:15	**Composite: Steel and concrete composite structures, material** Location: C204	**Connections 1: Connections** Location: C206	**Members 1: Columns** Location: C202
12:15 - 13:45	**Lunch** Location: Atrium		
13:45 - 15:30	**CFS1: Cold formed steel** Location: C204	**Connections 2: Connections** Location: C206	**Members 2: Beams** Location: C202
15:30 - 16:00	**Coffee Break** Location: Atrium		
16:00 - 17:30	**CFS2: Cold formed steel, sandwich panels** Location: C204	**Connections 3: Connections, welds** Location: C206	**Members 3: Beams, beam-columns** Location: C202
19:00 - 21:00	**Welcome Reception** National Technical Museum		

Thursday 12/9			
08:30 - 10:00	**K2: Keynote Lectures** Location: B286		
10:00 - 10:30	**Coffee Break** Location: Atrium		
10:30 - 12:15	**Fire 1: Fire** Location: C204	**PI1: Plates** Location: C206	**TC8_1: Session of ECCS TC8 – 1** Location: C202
12:15 - 13:45	**Lunch** Location: Atrium		
13:30 - 14:00	**Poster Session** Location: Atrium		
14:00 - 15:30	**Fire 2: Fire** Location: C204	**PI2: Plates: shear, patch loading; Shells** Location: C206	**TC8_2: Session of ECCS TC8 – 2** Location: C202
15:30 - 16:00	**Coffee Break / Poster Session** Location: Atrium		
16:00 - 17:30	**PI3: Shells** Location: C206	**TC8_3: Session of ECCS TC8 – 3** Location: C202	
19:00 - 21:00	**Conference Banquet** Location: Malostranský Palace		

Friday 13/9			
08:30 - 10:00	**Plenary Session + Tomáš Vraný SDSS Award** Location: B286		
10:00 - 10:30	**Coffee Break** Location: Atrium		
10:30 - 12:15	**CFS3: Cold formed steel, built-up members** Location: C202	**Seismicity: Seismic design** Location: C206	**Structures 1: Structures** Location: C204
12:15 - 13:45	**Lunch** Location: Atrium		
13:45 - 15:00	**CFS4: Cold formed steel** Location: C202	**Structures 2: Bridges** Location: C204	
15:00 - 15:30	**Closing Session** Location: C202		
15:30 - 16:00	**Conference Close and Farewell Drink** Location: Atrium		

Saturday 14/9	
08:30 - 17:00	**Optional Trip to Kutná Hora** Location: Kutná Hora

Abstracts

K1: Keynote lectures

Time: Wednesday, 11/Sep/2019: 9:00 am - 10:00 am · Location: B286
Session Chair: Todd Helwig, University of Texas at Austin
Session Chair: Dinar Camotim, Instituto Superior Técnico, University of Lisbon

9:00 am - 9:30 am

Structural steel design by advanced analysis with strain limits

Gardner, Leroy; Fieber, Andreas; Macorini, Lorenzo
Imperial College London, United Kingdom
Keywords: global analysis

The design of steel structures traditionally involves two key steps – firstly, a structural analysis is performed to determine the internal forces and moments in the structure, and secondly, design checks are carried out on the individual structural members to verify their stability. In design by advanced analysis, both material and geometric nonlinearities are captured during the analysis, hence eliminating the need for subsequent member checks. Only cross-section capacity checks are required. However, the structural analysis of steel frames is typically performed using beam elements. These elements are unable to explicitly capture local buckling, and hence current steel design specifications use the concept of cross-section classification to limit the strength and deformation capacity of a cross-section. This restricts the use of plastic design methods to Class 1 cross-sections, which possess sufficient rotation capacity for plastic hinges to develop. Local buckling prevents the development of plastic hinges for cross-sections with higher classes and, unless computationally demanding shell elements are used, elastic analysis is required. In all cases, the influence of strain hardening is ignored. A more sophisticated approach is set out herein. Firstly, an accurate material stress-strain model for hot-rolled steel, which allows for strain hardening, is described. Secondly, strain limits are employed in the advanced analysis to mimic the effects of local buckling. This allows cross-sections of all classes to be analysed in a consistent advanced analysis framework and to benefit from the appropriate level of force and moment redistribution, depending on the local slenderness of the cross-section. The approach has been applied to individual members, continuous beams and frames and has been shown to bring significant benefits in terms of accuracy and consistency over current steel design specifications.

9:30 am - 10:00 am

Advancements in the stability design of steel frames considering general nonprismatic members and general bracing conditions

White, Donald W.; Slein, Ryan; Togay, Oguzhan
Georgia Institute of Technology, United States of America
Keywords: nonprismatic members; structural stability

This paper presents an innovative approach for design of planar steel frames composed of prismatic and/or nonprismatic members. The method uses an inelastic eigenvalue buckling analysis configured with column, beam and beam-column inelastic stiffness reduction factors derived from the ANSI/AISC 360-16 Specification provisions to evaluate the member overall buckling resistances. The resulting procedure provides a relatively rigorous evaluation of all member strength limit states accounting for moment and axial force variations along the member lengths, nonprismatic geometry effects, general out-of-plane bracing conditions, and beneficial end restraint from less critical adjacent unbraced lengths and/or from end boundary conditions. The approach uses a pre-buckling analysis based on the AISC Direct Analysis Method to estimate the in-plane internal forces, including second-order effects. Given these forces, a buckling solution is conducted to evaluate the overall member stability. Other limit states are addressed by cross-section strength checks given the computed internal second-order analysis forces. Calculations from this approach are compared with results from recent experimental tests.

Composite: Steel and concrete composite structures, material

Time: Wednesday, 11/Sep/2019: 10:30 am - 12:15 pm · Location: C204
Session Chair: Ben Young, The Hong Kong Polytechnic University
Session Chair: Jakub Dolejš, CTU in Prague

10:30 am - 10:45 am

Ductility of Different Types of Shear Connectors - Experimental and Numerical Analysis

Gluhović, Nina; Spremić, Milan; Milosavljević, Branko; Marković, Zlatko; Dobrić, Jelena
University of Belgrade Faculty of Civil Engineering, Serbia
Keywords: shear connectors, ductility, composite structures

Different types of shear connectors which are used for achievement of composite action between steel and concrete have been developed during decades, in order to accomplish wide range of applications. Their suitability for various range of structures and loadings should accomplish different shear resistances, ductility of shear connectors, failure modes and fatigue resistances. Widely used shear connectors for composite constructions of buildings and bridges are headed studs and their design procedures can be found in different standards, such as EN 1994-1-1, ANSI/AISC-360-05 and JSCE. Bolted shear connectors, perforated shear connectors, mechanically fastened shear connectors or rebar couplers are alternative solutions for achievement of composite action between steel and concrete. Design resistances of these types of shear connectors are proposed by several authors. Results of experimental and numerical analysis of these types of shear connectors are used for comparative analysis of their different behaviour and presented in this paper. Three main characteristics of shear connectors, shear resistance, stiffness and ductility are specific for each type of shear connector. Comparative analysis presented in this paper included comparison of stiffness and different failure modes which can be noticed for these types of shear connections, with main focus on the ductility at different load levels. Also, the results are compared with current recommendation given in EN 1994-1-1 for deformation limits of ductile shear connectors.

10:45 am - 11:00 am

Experimental study on the shear connections of composite girders with trapezoidally corrugated web

Németh, Gábor; Jáger, Bence; Kovács, Nauzika; Kovesdi, Balazs
BME Department of Structural Engineering, Hungary
Keywords: shear connectors, composite girders, trapezoidally corrugated web, experimental study

Composite bridges made by steel beams and reinforced concrete slabs are the most economical choice for medium spans (40-60 m). Most commonly, headed studs welded to the upper flange of the beam are used as shear connector. Although the structural behavior of this type of shear connector is well known, the research of the last decades showed that connections made by concrete dowels can be more economical and have more favorable behavior. The application of corrugated web beams is also popular in composite structures, they can be applied with and without steel flanges beside the concrete slab. If no steel flange is used, the web is directly embedded into the concrete slab. This layout is applicable in both composite (upper concrete slab) and hybrid (upper and lower concrete slabs) structures. Experimental research program having large number (57 specimens) of full-scale push-out tests were performed in the Struc-tural Laboratory of the BME Department of Structural Engineering. The test program con-tained specimens with embedded web and specimens having steel flanges as well. The series of experimental tests made it possible to compare specimens with embedded corrugated web and specimens with upper steel flange with the aim to investigate the influence of the steel flange on the structural behavior of the connection resistance and deformation capacity. The current research program has the aim to experimentally investigate the structural behavior of shear connectors having concrete dowels or horizontal headed studs in steel-concrete compo-site girders with trapezoidally corrugated webs.

11:00 am - 11:15 am

Slim-floor beam bending moment resistance considering partial shear connection

Zhang, Qingjie; Schäfer, Markus
University of Luxembourg, Luxembourg
Keywords: slim-floor, steel and concrete composite

Having the advantage of flat lower surface, high stiffness and integrated fire resistance,slim-floor composite beams are widely used and favoured in many design solutions. The current bending design methods are mainly derived from plastic design methods for classical composite beam with consideration of the special features for slim-floor beams such as the transverse bending of bottom flange when used as support for slabs. Alternatively, more advanced strain-limited design method or FE-method can be used. In the case of full shear connection, with deep position of neutral axis and great compression zone height, there is a risk that plastic design method may overestimate the bending resistance of the cross section compared to the strain-limited design method. In the case of the partial shear connection, shear design diagram for slim-floor beams obtained by means of the strain-limited design can also differ significantly from the one obtained by plastic design method, thus further research on slim-floor beams is still necessary.

11:15 am - 11:30 am

Composite floor system with cold-formed trussed beams and prefabricated concrete slab

Leal, Luiz Alberto Araújo de Seixas; Batista, Eduardo de Miranda
Federal University of Rio de Janeiro, Brazil
Keywords: Steel and concrete composite floor system; Cold-formed steel member; Steel and concrete composite trussed beam; Shear connector; Structural experimental analysis

Composite steel and concrete floor systems are usual solution for building construction, conducting to reduce material consumption, improve structural strength and flexural stiffness. Steel frame light construction systems, based on combination of thin-walled cold-formed steel members (CFS) and panels (e.g wood, cementitious, gypsum plaster), may also benefit of composite behavior for the case of concrete slabs. In this context, full-scale experimental tests were conducted to evaluate the structural behavior of floor system conceived with 0.95-mm thick CFS trussed beams and pre-fabricated concrete slabs. Innovative solution for shear connectors was designed and tested, in order to ensure full interaction between the CFS trussed beam and concrete slab. Thin-Walled Channel connector (TWC) is based on lipped channel CFS attached to the top chord of the truss by self-drilling screws. Experimental results indicate efficient behavior of TWC shear connectors with improved bending capacity of the floor system.

11:30 am - 11:45 am

Behaviour of a concrete slab in compression in composite steel-concrete frame joints

Červenka, Petr; Dolejš, Jakub
Czech Technical University in Prague, Czech Republic
Keywords: steel-concrete, composite frames, composite joints, slab in compression, effective width

The objective of this research is a concrete slab in compression in composite steel-concrete joint. EN 1998-1 prescribes a simplified formula and it describes two mechanisms. The standard procedure for calculating the effective width of the slab is inaccurate, as it is stated repeatedly in a number of publications. Mechanism 1 acts in the concrete slab with a concentrated compressive force on the column flange. In the standard procedure for calculating the bearing capacity of this mechanism, the positive effect of the state of stress in the concrete slab in the joint region is not taken into account. The goal of this research is to derive more accurate formula for calculation of effective width of fibre-reinforced concrete slab in compression in the nodal zone. New aspects have been taken into account: confinement effect of the mechanism 1 and more precise inclinations of concrete struts. An experiments, a validation of a numerical models and a parametric study of the composite joints with slab made of common concrete and fibre-reinforced concrete are main steps of this research.

11:45 am - 12:00 pm

A reexamination of high strength steel Q690 plasticity model

Wang, Yuanzuo; Wang, Yanbo; Li, Guoqiang; Lyu, Yifan
Tongji University, People's Republic of China
Keywords: High strength steel; Plasticity model; Stress triaxiality; Lode angle

The most generally used yield function of typical metals, the von Mises yield function, shows that effects of stress triaxiality and Lode angle on the steel plasticity are negligible. However, this classical theory was challenged by Spitzig and Richmond who conducted an experimental study on various metal materials, and it showed that the effect of stress triaxiality and the Lode angle on the yield strength of some typical metals should be considered. In the present paper, experiments and finite element analyses are carried out to evaluate the effect of stress triaxiality and Lode angle on the plastic behavior of Chinese high strength steels (HSS) Q690, and the application of von Mises yield criterion is examined using finite element analyses. Results demonstrate that an appropriate yield function of the HSS should consider effects of the Lode angle and the influence of stress triaxiality is negligible. Based on experimental and simulation results, a new yield function for HSS is proposed, to essentially simulate the experimental results via user subroutine in ABAQUS.

12:00 pm - 12:15 pm

Calibration of parameters of combined hardening model using tensile tests

Zub, Ciprian Ionut; Stratan, Aurel; Dubina, Dan
Politehnica University of Timisoara
Keywords: calibration, combined hardening model, Abaqus, mild carbon steel, tensile tests

When performing finite element simulations on structural steel elements, proper modelling of the uniaxial cyclic response of the material is necessary for numerical simulations with a high level of reliability. Good predictions of the cyclic response of steel in the plastic range can be obtained if using the combined isotropic-kinematic hardening model. The calibration of material parameters of the combined model using cyclic test data requires good knowledge of the metal plasticity theory and the implementation of the model into the finite element software used within the simulations (Abaqus). Moreover, experimental coupon tests using cyclic loading are more difficult to be performed and requires special care to prevent buckling. Therefore, a simplified calibration procedure of the material parameters using tensile test data is presented in this paper. Both the kinematic and the isotropic parameters are obtained from the tensile test data, using an analytical calibration procedure. The material parameters obtained this way allow for predictions with a good level of correlation, for both monotonic and cyclic loading conditions. These predictions are validated against experimental tests performed on S355 mild carbon steels.

Connections 1: Connections

Time: Wednesday, 11/Sep/2019: 10:30 am - 12:15 pm · Location: C206
Session Chair: Jean-Pierre Jaspart, Liège University
Session Chair: Martina Eliášová, Faculty of Civil Engineering, CTU in Prague

10:30 am - 10:45 am

Numerical Study of End-Plate Steel Connections with Two and Four Bolts-per-Row

Nunes, Daniel Luís; Ciutina, Adrian
University Politehnica of Timisoara, Romania
Keywords: ductility, 4-bolt-rows, end-plate connections, FEM analysis, beam-to-column connections

The classic technical solution of beam-to-column connections with extended end-plate with two bolts-per-row has a well-established behaviour and its design is finely defined in the Eurocodes. It has, however, several limitations in situations where there is a depth limit or in case of extreme actions. As a solution to theses particular cases, a configuration with four bolts-per-bolt may provide the necessary characteristics in order to improve the performance of the connection and therefor, of the entire structure. However, several studies already have shown that the classic t-stub analysis may not accurately describe this connections' behaviour, as the failure modes do not follow a row-by-row progression. In this context, a set of relevant numerical models of the tensioned area of the connection (the first two bolt-rows, representing the tensile macrocomponent) was developed for both solutions with two and four bolts-per-row, with varying parameters for end-plate thickness, bolt diameter and flange width. The subsequent FEM analysis aims to reveal the change in the connection's behaviour with the variation of the different parameters.

10:45 am - 11:00 am

Experimental Study of Beam-to-Column Connection with Bolted Joints

Koyama, Yohei[1]; Sato, Atsushi[1]; Sato, Yuki[2]; Yagi, Shigeharu[2]; Idota, Hideki[1]; Takaki, Sunao[3]; Kamada, Manabu[3]

[1]Nagoya Institute of Technology, Japan; [2]IIJIMA Structural Design Office; [3]Sumikin System Buildings Co.LTD.

Keywords: beam-to-column connection, bolted joints, wide-flange section, panel zone, T-stub

It is common to use a steel hollow structural section for the columns in Japan; however, it also common to use the wide-flange section for the columns to connect the beams by high-strength bolts in the industrial buildings' systems. When the wide-flange section is used for the column, the dissipative zone might be assumed in the panel zone when the doubler plate is not installed. It is also well known that in-elastic behavior in the panel zone can provide stable performance; it can be used to absorb the energy to avoid the collapse of the structure. Although the contribution of the plastic deformation at the panel zone is limited up to 30% in Eurocode 8, there is no limit in the Japanese code when the structural performance is verified.

In this paper, full-scale testing of the beam-to-column connections where the beam is connected to the column though T-stub by high-strength bolts are tested. Welding which is typical in the connection region is not used in the tested specimens. High-strength bolts joints are also used to install the continuity plates that should be used to stiffen the local deformation of the column flange. From the testing, the maximum strength, and the deformation capacity of the beam-to-column connection will be evaluated. In the tested specimens, the shape similar to T-stub is used for the continuity plate, and partial reinforcement at the panel is happening; therefore, the region of the panel zone shall be needed to define. From the testing following results were found.

Firstly, the structural performance of the beam-to-column connection with bolted joints was shown. Total of four specimens were conducted. The test results clearly showed that the specimens where the panel zone shall be the dissipative zone can provide stable in-elastic behavior, and strength degradation occurred after the story drift goes beyond 4.0%.

Secondly, bolt slippage was not found in the bolt joints where it was adequately designed based on the demand force.

Thirdly, panel zone region where the bolted continuity plates are used can be defined from the configuration of the connected bolt location.

Finally, it was proved that the proposed beam-to-column connection can be used as the dissipative zone system.

11:00 am - 11:15 am

Comparison of two different Innovative Solutions for IPE Beam to CHS Column Connections

Das, Rajarshi[1]; Kanyilmaz, Alper[2]; Degee, Herve[1]
[1]Construction Engineering Research Group, Universiteit Hasselt, Belgium; [2]Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italy
Keywords: Beam-to-CHS connection, Plate-to-CHS connection, CHS joints, Hollow section joints, Passing-through joints

Local stiffeners and gusset plates used in conventional open-to-Circular Hollow Section (CHS) column connections result in high welding quantities, whereas direct welding ex-poses the CHS to severe local distortions. Such disadvantages hinder the use of open-to-CHS column connections. To minimize these drawbacks and improve the structural be-behavior, this study proposes two moment resisting connection configurations developed within the European research project "LASTEICON". It deals specifically with I-beam resp. individual plates passing through the CHS column. The "passing-through" system is made possible by resorting to an easy fabrication process thanks to efficient laser cut & weld technology and avoids the localized damages, premature flange failures and excessive use of stiffening plates required by the conventional I-beam-to-CHS column connection configurations. The new configurations are investigated for two different load cases with experimentally calibrated nonlinear finite element models and are also compared among each other to differentiate the force-transfer mechanism involved.

11:15 am - 11:30 am

Modelling of one-sided unstiffened beam-to-column joint

Zamorowski, Jan[2]; Gremza, Grzegorz[1]
[1]Silesian University of Technology, Poland; [2]The University of Bielsko-Biała, Poland
Keywords: component method, equivalent T-stub, joint capacity and stiffness, joint modelling

Conducted numerical and experimental tests indicate that in the case of the end-plate joint of a beam to an unstiffened column with several bolt rows, the load capacity of the bolts in the row below the tension flange of the beam may be exceeded at the value of the bending moment lower than design moment resistance of these joint determined according to the formula (6.25) in EN 1993-1-8. Meanwhile, the bearing capacity of the bolts in the row placed outside the tension flange of the beam will be sufficient. This follows the fact that the resistance of the inner bolt row is usually determined by the resistance of the column flange in bending, the effective length of which is small compared to the effective length of the flange in the area of the end bolt-row. In turn, this length has a much lesser influence on the stiffness of the T-stub reproducing/imitating the inner bolt-row. In such cases, there is a need to reduce the design resistance

of the joint, in order that the forces in the inner bolt row not exceed the capacity of the stub which imitates this rows.

The EN 1993-1-8 standard does not contain a description of the joint's calculation model, on the basis of which one could determine the forces in individual bolt rows. However, there is a rule provided in point 6.2.4.2 (3) which commit to ensure that forces transmit-ted by individual bolt rows and groups of these rows do not exceed the design load capacities of a rows and a group of bolt rows. The algorithms in available computer programs used in design of such joints usually do not include the requirements included in aforementioned rule. It seems that it would be advisable to reword the standard in this regard. This would allow the complementation of the computer programs and the safe design of such joints.

The work will present an example of a constructional solution of a joint, on the basis of which the problems related to the above-mentioned issue will be discussed.

11:30 am - 11:45 am

Experimental tests on bolted end-plate connections using thermal insulation layer attached to steel structures

Couchaux, Maël[1]; Ahlasawi, Anas[1]; Ben Larbi, Amor[2]
[1]INSA Rennes, France; [2]CTICM, France
Keywords: Building; thermal performances; steel structure; thermal bridging; thermal break; analytical model; mechanical tests

This paper deals with the mechanical performances of thermal break for external steel structures (balconies, passageways) attached to a steel facade with external thermal insulation. The proposed solution is composed of a PVC or wood plate inserted between an end-plate connection and a steel column. Static and cyclic tests are performed on a cantilever beam connected to a steel column by a thermal break in order to investigate the effect of the thermal insulation layer on the rotational stiffness, bending moment resistances and failure modes. These tests highlight on one hand the influence of the thermal insulation and on another hand, the bolt configuration (extended and flush end-plate, stiffeners, RHS or I profile).

11:45 am - 12:00 pm

Influence of geometrical imperfection of rib stiffeners on beam-to-column joint behaviour

Tartaglia, Roberto; D'Aniello, Mario; Di Lorenzo, Gianmaria; Landolfo, Raffaele
University of Naples Federico II, Italy
Keywords: finite element analysis, steel structures, dissipative connections, construction imperfections

The introduction of rib stiffeners in the extended end-plate joints can guarantee a beneficial increase of both the strength and ductility of the connection. Indeed, the presence of the rib influences the yield line distribution in the tensile zone of the connection, the depth of internal lever arm as well as the resistance of compression components of the joint . However, unexpected phenomena can develop if the stiffeners are not properly aligned with the beam web. Therefore, in this work, a parametric finite element (FE) analyses was conducted to investigate the influence of the rib constructional imperfection on both the local and global joint response. In particular, the variation of the compression center position and the development of additional internal actions in the bolt rows was monitored for five different rib misalignments. The results show that some geometrical imperfections could have a beneficial effect on the joint capacity limiting the beam out-of-plane mechanism when the plastic hinge develops at the beam extremity.

12:00 pm - 12:15 pm

Behavior of extended end-plate connections under cyclic alternate loading

Tomăscu, Ioana Cristina; Bâlc, Roxana Maria
Technical University of Cluj-Napoca, Civil Engineering Faculty, Romania
Keywords: end-plate connections, cyclic loading, numerical model, analytical model, experimental model, moment-rotation curve

Behavior of steel frame structures, subjected to static and dynamic loadings, extensively studied over the past decades, can be controlled and influenced by the connections configuration. Thus, special attention has been paid over the years to the evaluation of the three basic characteristics of steel connections, strength, stiffness and ductility, and their impact on the global structure behavior. Starting from this, the present paper introduces a study of a beam-to-column bolted stiffened double extended end-plate connection. Based on the experimental and numerical models and through a parametric study, analytical models capable of describing its behavior have been established. Following the nonlinear analysis carried out in ABAQUS, the cyclic behavior of the connection was evaluated in terms of stress distribution, its equivalent plastic strain, local phenomena evolution and moment-rotation curves. The results of these studies are analyzed and compared, and finally some conclusions can be drawn regarding the behavior of this typology of joints.

Members 1: Columns

Time: Wednesday, 11/Sep/2019: 10:30 am - 12:15 pm · Location: C202
Session Chair: Luís Simões da Silva, University of Coimbra
Session Chair: Mark Andrew Bradford, UNSW Sydney

10:30 am - 10:45 am

Buckling behavior and strength of corroded steel shapes under axial compression

Hisazumi, Kazumasa[1]; Kanno, Ryoichi[2,1]
[1]Nippon Steel Corporation, Japan; [2]Kanazawa University, Japan
Keywords: corrosion, steel shapes, buckling strength, uniaxial compression tests, FE analyses

Corrosion is one of the most serious threats to the sustainability of steel structures, especially for those exposed to the atmosphere and subjected to improper maintenance management. Typical steel structures are bridges, transmission line towers, and conveyer-supporting frames. As corrosion-related problems and accidents have been frequently reported in recent years, the need for identifying the health condition of structures has increased. In this context, the axial compressive strength of corroded steel shapes is investigated with experiments and non-linear finite element analyses. The results indicate that the behavior of the corroded members depends strongly on the degree of corrosion and shows global flexural buckling, local buckling, section yielding, and combined failure modes. A strength formula considering the interaction between global and local buckling is proposed, showing that it can reasonably be used for estimating the strengths of corroded shapes.

10:45 am - 11:00 am

Explanatory notes to buckling design of longitudinally welded aluminium compression members

Misiek, Thomas[1]; Norlin, Bert[2]; Höglund, Torsten[2]
[1]Breinlinger Ingenieure, Germany; [2]Royal Institute of Technology, Sweden
Keywords: aluminium, buckling curve

As part of the ongoing revision of the Eurocodes, the regulations in EN 1999-1-1 on the buckling of aluminium compression members were also subjected to a critical review. This resulted in the need to revise the regulations for non-welded compression members and for longitudinally welded compression members.

For the design provisions of longitudinally welded aluminium compression members, a more extensive revision was necessary. The design concept was completely revised. In the course of the revision, some quite complex design models were discussed with which the cross-section types, residual stress distributions as well as size and position of the heat-affected zone (HAZ) were to be taken into account. In order not to complicate the application of the standard too much (ease of use), a clearly simplified procedure was finally chosen. The following contribution will justify these simplifications.

11:00 am - 11:15 am

Experimental Calibration of Centrally Loaded Built-up Battened Compression Members

El-Mahdy, Ghada
The British University in Egypt (BUE), Egypt
Keywords: calibration, experimental methods, built-up columns, codes, finite element

There is a large diversity in the requirements for designing built-up compression members between international design codes. Most codes, including the North American standards and specifications specify the use of an equivalent or modified slenderness ratio. In general, all North American standards and specifications agree on the need of using a modified slenderness ratio, but differ in the factor used to multiply the local slenderness ratio. Theoretically it is difficult to estimate the exact value of this factor, and using experimental methods does not capture the exact value of this factor either. Hence, a different approach is needed to determine the value of this factor. In this paper an experimental method to determine the exact value of the modified slenderness ratio of a built-up compression member by comparing it to the slenderness ratio of a solid column is given. The results are further illustrated using finite element modeling.

11:15 am - 11:30 am

Simulation based imperfections and their effects on stability resistance

Budaházy, Viktor; Kollár, Dénes; Vigh, László Gergely
Budapest University of Technology and Economics, Hungary
Keywords: simulation of fabrication process, axially loaded tube, shell buckling, numerical computation of imperfections, GMNIA

The fabrication process of a steel structural member fundamentally determines its imperfections. The accuracy of cutting, the spring-back during cold forming, and the specification of welding procedure leads to residual stresses and distortions. In design according to the Eurocodes, engineer can use the equivalent geometric imperfections in geometrically and materially nonlinear analysis simulation. In certain cases, it is difficult to determine the amplitude of equivalent geometric imperfections, which can take the fabrication process into account, and the detailed knowledge of the stress and distortion can result in a more accurate design process. Primary aim of this paper is to illustrate the methodology of simulation based imperfection analysis and resistance computation, as well as to discuss the applicability of the method. In the paper, the calculation of axially compressed, cold-formed and welded members is presented, where the total fabrication and loading process are investigated based on numerical simulations. We compare the resistance of the member using equivalent geometric imperfections and considering the complete fabrication process.

11:30 am - 11:45 am

Experimental Investigation of Compressed Stainless Steel Angle Columns

Filipović, Aljoša[1]; Dobrić, Jelena[1]; Marković, Zlatko[1]; Baddoo, Nancy[2]; Spremić, Milan[1]; Fric, Nenad[1]
[1]University of Belgrade Faculty of Civil Engineering, Serbia; [2]Steel Construction Institute, United Kingdom
Keywords: stainless steel, angle section, hot-rolled, laser-welded, cold-formed, compression, experiment, buckling

This paper presents the experimental programme of an extensive research project that deals with analysing the behaviour of compressed stainless steel columns with equal angle sections. The research focuses on different material and geometrical parameters of pin-ended angle columns produced from austenitic and lean-duplex stainless steel alloys. To assess influences of initial imperfections on column compressive resistance caused by different manufacturing procedures, three types of angle products are included: cold-formed, hot-rolled and laser-welded sections. In order to obtain both elastic and inelastic ultimate responses, including flexural and torsional-flexural buckling modes, the lengths and cross-section geometry of specimens are selected to cover non-slender sections and slender sections covering the entire wide

slenderness range. The experimental programme covers all relevant tests: 15 tensile coupon tests, 15 stub-column tests, 48 overall buckling tests of slender columns and 2 residual stress tests, including measurements of initial geometric imperfections. The purpose of these experiments is to establish a reliable database which can be used for numerical parametric analyses. Following the extensive experimental and numerical investigations, buckling curves for angle members manufactured by different processes are developed. Hence, the important innovative content of the project relates to the extension of the scope of currently codified procedures in EN 1993-1-4 not only to conventional angle profiles, but also to the contemporary products such as laser-welded angles.

11:45 am - 12:00 pm

Buckling of columns during welding

Vild, Martin; Bajer, Miroslav
FAST VUT, Czech Republic
Keywords: column buckling, experiment, welding

The paper presents experiments of columns loaded by compressive force during welding along their longitudinal axis. The weld bead was being laid in the corner of the cross-section from the bottom to the mid-height at the constant load. Then, still during welding, the load was being increased until the column failed by flexural buckling. Gas metal arc welding with carbon dioxide was used. All the columns had the height of 3 m. The tested cross-sections were HEA 100, IPE 120, IPE 160, SHS 100×5, and CHS 76×4. The measured values were the applied load, column deflections and changes in length, welding voltage, current and speed, and temperatures. The experiments were performed at the laboratory of Department of Metal and Timber Structures of Faculty of Civil Engineering of Brno University of Technology. The material properties of steel are temporarily decreased by the high temperature caused by the welding process. The method is offered to design the buckling resistance of a column during welding. The cross-sectional properties are assumed to be reduced at the most dangerous height and the column is treated as stepped. The deflection caused by the shrinkage of asymmetrically placed welds should be also taken into account.

12:00 pm - 12:15 pm

Study on the Out-of-Plane Stability of Steel Portal Frames

Vassilev, Marin; Rangelov, Nikolaj
Department of Steel and Timber Structures, UACEG, Sofia, Bulgaria
Keywords: Portal frames, Lateral stability, GMNIA, Experiments, Imperfections

Despite the extensive application of steel portal frames for single-storey buildings, there are still some aspects of their stability that require additional clarification. No codified practical method is specified in EN 1993-1-1 for lateral-torsional buckling verification of rafters in the haunched portions loaded by hogging bending moments. It seems that, within the code, there are only two possible approaches: the general method for lateral and lateral-torsional buckling, and the geometrically and materially nonlinear analysis with imperfections (GMNIA). However, both methods seem quite complicated and cumbersome for practical use. Therefore, an algorithm and corresponding software for automatic modelling and applying both the general method and GMNIA have been developed.

To validate the numerical simulations, an experimental programme is carried out on three full-scale portal frames of hot-rolled profiles. The experimental results are compared with those from the numerical simulations of the test frames and a very good compliance has been found. On this basis, GMNIA is proven as benchmark method of numerical analysis. Within this context, a substantial positive effect of the initial imperfections with various patterns is found, compared to the case with the most unfavourable imperfection pattern based on the first out-of-plane buckling mode.

An extensive parametric study is conducted on thousands of portal frames composed of hot-rolled profiles. Practical conclusions on the influence of various factors are drawn. An important finding based on the comparative analysis is that the application of the general method to whole plane portal frames appears non-conservative and therefore its use shall be limited to single members. Based on the obtained results and conclusions drawn, simple design rules for practical application are suggested by adapting the well-known equivalent compressed strut model.

CFS1: Cold formed steel

Time: Wednesday, 11/Sep/2019: 1:45 pm - 3:30 pm · Location: C204
Session Chair: Viorel Ungureanu, Politehnica University of Timisoara
Session Chair: Ivan Balázs, Brno University of Technology, Faculty of Civil Engineering

1:45 pm - 2:00 pm

FEM analysis of the buckling behaviour of thin-walled CFS columns. Part I - Channel (C) and Double Channel (I) cross-sections

Craveiro, Helder D.[1]; Henriques, José[2]; Silva, Luís Simões[1]; Martins, João P.[1]
[1]ISISE - Institute for Sustainability and Innovation in Structural Engineering, University of Coimbra Portugal; [2]CERG – Construction Engineering Research Group, Faculty of Engineering Technology, University Hasselt, Belgium
Keywords: cold-formed steel, buckling, finite element, parametric

The demand for structures using cold-formed steel (CFS) sections has increased significantly since it has been recognized as a valuable and competitive structural solution. One of the main advantages of thin-walled CFS profiles is the "freedom" the designer has to conceive a cross-section shape tailored for the structural application. Consequently, different cross-sections shapes have been developed and may be found in the market. Furthermore, the combination of thin-walled CFS profiles, in the form of built-up cross-section members, further increases the range of available options. On the other hand, this diversity of solutions brings a challenge to the designer, as for some uncommon cross-section shapes, the mechanical behaviour is not entirely known and therefore not covered in the design codes. In the particular case of built-up cross-sections, the connections between the profiles play an important role in the local and global behaviour of the member. Though this type of cross-sections is nowadays very common in the construction of thin-walled CFS structures, very few information is found in the Eurocode for the design of this type of members. Hence, in this paper, the buckling behaviour of thin-walled CFS columns is investigated by means of FEM. The numerical models were developed and calibrated using experimental results on lipped channels and open built-up I cross-sections (two-lipped channels fastened back-to-back on the web). Upon validation, a parametric analysis is performed, to further assess the influence of different parameters, such as steel thickness, material grade, cross-section dimensions, boundary conditions and connection spacing, in the case of the built-up cross-section.

2:00 pm - 2:15 pm

FEM analysis of the buckling behaviour of thin-walled CFS columns. Part II - Monosymmetric (R) and doubly symmetric built-up box cross-sections.

Craveiro, Helder D.[1]; Henriques, José[2]; Silva, Luís Simões[1]; Martins, João P.[1]

[1]ISISE – Institute for Sustainability and Innovation in Structural Engineering, Department of Civil Engineering, University of Coimbra, Portugal; [2]CERG – Construction Engineering Research Group, Faculty of Engineering Technology, University Hasselt, Belgium

Keywords: cold-formed steel, buckling, built-up, finite element, parametric

The demand for structures using cold-formed steel (CFS) sections has increased significantly since it has been recognized as a valuable and competitive structural solution. One of the main advantages of thin-walled CFS profiles is the "freedom" the designer has to conceive a cross-section shape tailored for the structural application. Consequently, different cross-sections shapes have been developed and may be found in the market. Furthermore, the combination of thin-walled CFS profiles, in form of built-up cross-section members, further increases the range of available options. On the other hand, the diversity of solutions brings a challenge to the designer, as for some uncommon cross-section shapes, the mechanical behaviour is not entirely known and therefore not covered in the design codes. In the particular case of built-up cross-sections, the connections between the profiles play an important role in the local and global behaviour of the member. Though this type of cross-sections is nowadays very common in the construction of thin-walled CFS structures, very few information is found in the Eurocode for the design of this type of members. Hence, in this paper, the buckling behaviour of thin-walled CFS columns is investigated by means of FEM. In the present paper, the second part of a numerical study on the subject is presented. Columns consisting of the monosymmetric built-up box cross-section (R-section) and doubly symmetric built-up box cross-section (2R-section), comprising lipped and plain channels are investigated. For the validation and calibration of the FEM model, an experimental campaign on thin-walled CFS columns using these cross-section shapes, conducted at the University of Coimbra, was considered. Upon validation of FEM, a parametric analysis is performed to further assess the influence of different parameters, such as steel thickness, material grade, cross-section dimensions, boundary conditions and connection spacing.

2:15 pm - 2:30 pm

On the Incorporation of Cross-Section Restraints in Generalised Beam Theory

Gonçalves da Silva, Thiago[1]; Basaglia, Cilmar[1]; Camotim, Dinar[2]
[1]Department of Structural Engineering, School of Civil Engineering, Architecture and Urban Design, University of Campinas, Brazil; [2]Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
Keywords: Thin-walled members, Generalised Beam Theory (GBT), Cross-section restraints, Deformation modes, Buckling behaviour

In Generalised Beam Theory (GBT), which incorporates genuine plate theory concepts, the cross-section displacement field is expressed as a linear combination of deformation modes, making it possible to write the equilibrium equations and boundary conditions in an unique and very convenient format. In practical applications, thin-walled members are often continuously restrained along their lengths - e.g., purlin-sheeting and sheathed wall stud systems. In order to incorporate such (elastic) restraints in a GBT analysis, two approaches can be followed: (i) incorporate the restraints in the cross-section analysis, taking them into account at the deformation mode determination stage or (ii) include the restraints only in the member analysis, which means that the deformation modes are calculated without considering the restraints (code GBTUL2.0 adopts this last approach, which involves combining the conventional deformation modes only at the member analysis stage). This paper reports the available results of an ongoing investigation on the development of a GBT formulation intended to render the buckling analysis of thin-walled restrained members more efficient and illuminating. It is based on a cross-section analysis procedure that incorporates the elastic restraints, thus leading to the determination of restrained deformation modes. The application and capabilities of the proposed GBT formulation are illustrated through the presentation and discussion of illustrative numerical results concerning cold-formed steel (i) studs braced by sheathing and (ii) purlins restrained by sheeting. For validation and assessment purposes, some results are compared with values yielded by the codes GBTUL2.0 (conventional GBT) and/or ANSYS (shell finite element analysis). Besides the expected virtually coincident results, it is shown that the proposed GBT formulation is much more efficient than the conventional one. In particular, it becomes possible to obtain accurate buckling results with a single deformation mode, which enables the development of analytical formulae to calculate critical buckling loadings of restrained members.

2:30 pm - 2:45 pm

Local-distortional buckling interaction of cold-formed steel columns design approach

Batista, Eduardo de Miranda[1]; Matsubara, Gustavo Yoshio[1]; Franco, Juarez Moara dos Santos[2]

[1]Federal University of Rio de Janeiro, Brazil; [2]Federal Rural University of Rio de Janeiro, Brazil

Keywords: Cold-formed steel structures, Interaction buckling mode, Experimental analysis, Finite element model, Design procedure

Local-distortional interaction buckling mode (LD) in steel cold-formed (CFS) columns is the objective of the present research. Experimental and FEM results are the basis of the original design proposition, based on both the direct strength method (DSM) and the Winter-type strength equation. The present results represents improvement of solution recently published by the authors, with modified equations bringing more simple formulation as well as keeping acceptable structural safety condition. The proposed solution offers strength surface bridging the widely accepted DSM solutions for local and distortional buckling. This concept is based on the main variable of LD interaction of lipped channel columns, the ratio between distortional and local buckling slenderness factor. After identification of the range of the factor for which columns are significantly affected by the LD interaction, the Winter-type surface equation is calibrated with the help of experimental data and FEM results.

2:45 pm - 3:00 pm

Direct Strength Method (DSM) design of end-bolted cold-formed steel columns failing in distortional modes

Santos, Warlley Soares[1]; Landesmann, Alexandre[1]; Camotim, Dinar[2]

[1]Civil Engineering Program, COPPE, Federal University of Rio de Janeiro, Brazil.; [2]CERIS, ICIST, DECivil, Instituto Superior Técnico, Universidade de Lisboa, Portugal.

Keywords: Cold-formed steel lipped channel columns, Bolted end support conditions, Distortional failure, Experimental investigation, Direct Strength Method (DSM) design

This work reports the results of an experimental and numerical investigation concerning the influence of bolted end support conditions on the behaviour and ultimate strength of cold-formed steel lipped channel columns buckling and failing in distortional modes, as well as on their prediction by means of the Direct Strength Method (DSM). This type or end support conditions, commonly used in the civil engineering construction industry, consists of pairs of cylindrical high-strength bolts with hexagonal heads and nuts, which are inserted in two standard-size holes located at the intersections of the flanges with the principal centroidal axis parallel to the web. After describing the ANSYS SFE model used to acquire knowledge about the column non-linear behaviour, strength and collapse, numerical failure loads are obtained and presented. Together with the

experimental failure loads previously reported by the authors, these numerical failure loads are then employed (i) to assess the merits of the available DSM column distortional design curves and, after their inadequacy is shown, (ii) to develop and validate new strength curves, aimed at providing efficient predictions for the whole failure load set considered. Two preliminary proposals are put forward and shown to yield quite reasonable and very similar failure load predictions: (i) a modification of a design curve previously proposed by authors, which has the non-negligible drawback of requiring a rigorous critical distortional buckling load calculation, by means of sophisticated contact SFE models, and (ii) the use of this same design curve, but expressed in terms of a slenderness based on critical distortional buckling loads of "ideal pin-ended columns" with lengths equal to the distance between the bolt centre lines, which can be calculated straightforwardly. One last word to mention that further work on this topic is currently under way and should be reported by the authors in the near future.

3:00 pm - 3:15 pm

Experimental and numerical analysis of the local and interactive buckling behaviour of hollow sections

Toffolon, Andrea[1]; Müller, Andreas[1]; Niko, Igor[2]; Taras, Andreas[1]
[1]Bundeswehr University Munich, Institute of Structural Engineering, Germany; [2]Slovak University of Technology, Dept. of Steel and Timber Structures, Slovakia
Keywords: local buckling, interactive buckling, hollow sections, imperfection analysis, reverse engineering

Inadequate knowledge regarding specific local and interactive behavior of slender high-strength steel (HSS) hollow sections presents an obstacle in implementing these sections in the construction practice. The current approach in the standard is simplified and offers overly conservative results. Dealing with non-standard cross-sections only expands on these difficulties.

This paper contributes to the on-going RFCS project "HOLLOSSTAB", which has been dealing with the aforementioned issues. The project design proposal is based on the "Overall interaction concept" (OIC), and a new set of design rules for hollow sections is currently being developed. In this concept, linear buckling analysis (LBA) is used to obtain the slenderness of the member, and Geometrically and Materially Non-linear Imperfection Analysis (GMNIA) is used to determine an "overall" buckling reduction factor. Extensive experimental tests are used to validate the method, by correlating the experimental results with numerical test results (GMNIA-real) and statistically analyzing them. The focus of the tests in this paper is the use of high-strength steel, ranging from S500 to S890, used for cylindrical hollow-sections, rectangular hollow-sections and hexagonal hollow-sections.

The state-of-the-art measuring tools available offer the possibility of precise reverse-engineering process, creating a numerical model of experimental test. It is possible to reach an accurate prediction of ultimate load capacity of the

specimen. The buckling shape can also be checked, using digital image correlation (DIC), comparing numerical model with real shape of tested specimen.

The paper aims to validate the numerical models, as well as validity of assumptions on imperfection amplitude.

3:15 pm - 3:30 pm

Progressive collapse assessment of storage racks due to localized failures. Explicit consideration of dynamic effects

Marginean, Ioan; Dinu, Florea; Dubina, Dan
Politehnica University Timisoara, Romania
Keywords: robustness, impact, progressive collapse, tying action, upright

Storage rack structures are light metal structures, with elements made of thin-walled sections, mostly cold formed, and with pinned or partial-strength/semi-rigid connections (up-right base, beam-upright). Due to low redistribution capacity and special gravity load conditions (storage structure), any local damage in elements or connections can spread to neighboring elements, generating extensive damage or even generalized collapse (progressive collapse). The analysis and design of the rack structures is laborious, especially due to the characteristics of the sections and connections (thin-walled sections, perforations on uprights, nonlinear response of connections). Because of these peculiarities, reference cannot be made to usual structural design recommendations and standards and additional rules are required for modeling, analysis and design of racks. The accidental impact of transport and lifting equipment (forklift trucks) is one of the main sources of risk for the stability and integrity of rack structures. In the study, robustness of Selective Pallet Rack structures (SPR) in case of accidental impact was evaluated. The response was compared with the more conventional column (upright) loss approach employed by means of both static and dynamic analyses. Structural configurations vary by considering different properties of connections (upright base, beam-upright). The results have shown that upright removal can generate global failure, if the stiffness of connections is low (pinned or semi-rigid). Also, upright loss approach can provide satisfactory results with less computational effort, but there are additional effects that require further corrections.

Connections 2: Connections

Time: Wednesday, 11/Sep/2019: 1:45 pm - 3:30 pm · Location: C206
Session Chair: Atsushi Sato, Nagoya Institute of Technology
Session Chair: Adrian Ciutina, Politehnica University of Timisoara

1:45 pm - 2:00 pm

Tests of gusset plate connection under compression

Vesecký, Jan; Cábová, Kamila; Jandera, Michal
Czech Technical University in Prague, Czech Republic
Keywords: gusset plate, connection, tests, experiments, stability, buckling, plastic hinges, analytical model

Over the past years, research has shown, that behavior of connections with gusset plates subjected to compression represents a complicated task. There has been developed a few analytical methods since then, some of which are used in standards procedures, mainly in Australia, New Zealand and Canada. However, in European standards, no design procedure is described and EN 1993-1-5 offers only general rules for buckling of steel plates. This paper introduces four analytical models used for gusset plates design – Whitmore, Thornton, Modified Thornton and model proposed by Khoo, Perera and Albermani. Furthermore, results of new experimental study on six full scale specimens are presented. Among other measuring methods, 3D digital image correlation was used for detection of planar strain of plates. Finally, experimental results are compared to predictions of analytical models. It is shown, that all methods based on dispersion angle are completely inappropriate for this type of connections.

2:00 pm - 2:15 pm

Numerical modelling of gusset plate connections under eccentric compression

Vesecký, Jan; Jandera, Michal; Cábová, Kamila
Czech Technical University in Prague, Czech Republic
Keywords: gusset plate, connection, stability, buckling, numerical model, parametric study, validation

Recently, new experimental study which was focused on behavior of bolted connections with gusset plate under eccentric compression was carried out at CTU in Prague. Buckling resistance and longitudinal and lateral deflection was measured for six specimens. The specimens represented full scale tubular bracing connected to rigid load-bearing construction on both ends. Progressive 3D digital image correlation technology was used, to record planar strain of plates. This paper describes complex numerical models based on aforementioned physical specimens. General FEA software Abaqus including geometric and material nonlinearities (large deformations, plasticity, imperfections) was used. Numerical models were validated on results measured during experiments. Later, an extensive parametric study was performed with

nearly 50 numerical models. Influence of total of eight free parameters was examined. Besides other results, parametric study confirmed previous findings, that analytical models based on dispersion angle are generally not accurate for design of eccentric gusset plate connections.

2:15 pm - 2:30 pm

Design of gusset plate connection with single-sided splice member by component based finite element method

Vild, Martin[1]; Kuříková, Marta[2]; Kabeláč, Jaroslav[1]; Wald, František[2]
[1]Brno University of technology, Czech Republic; [2]Czech Technical University in Prague, Czech Republic
Keywords: steel structures, connection, buckling, component based finite element method

This paper describes the design of the single-sided gusset plate connection of a truss steel member by a component based finite element method. The elements are analysed by geometrically and materially non-linear analysis. The proper behaviour of components, e.g. of bolts, anchor bolts, welds, is treated by introducing components representing its behaviour in term of initial stiffness, ultimate resistance and deformation capacity. Research oriented finite element model is validated on experiments. The models are analysed by geometrically and mate-rially non-linear analysis with imperfections. The research oriented model is compared with simplified design one, which includes only the joint and equivalent horizontal disruptive force. Contribution shows the current trends in advanced modelling of connection components and differences of the research oriented and design oriented finite element models. The upcoming models with coupling of member and its joints are shown on this single-sided gusset plate connection.

2:30 pm - 2:45 pm

Design of slender compressed plates in structural steel joints by component based finite element method

Kuříková, Marta[1]; Wald, František[1]; Kabeláč, Jaromír[2]
[1]Czech Technical University in Prague, Czech Republic; [2]Brno University of technology, Czech Republic
Keywords: steel structures, connection, buckling, component based finite element method

This contribution shows the current trends in advanced modelling of connections and differences of the research oriented and design oriented models. The principles of Component Based Finite Element Modelling and the system response quantity and application features for de-sign of slender compressed elements was developed. The elements are analysed by material non-linear and by buckling analyses. The proper behaviour of components, e.g. of bolts, anchor bolts, welds etc., is treated by introducing components representing its behaviour in term of initial stiffness, ultimate resistance and deformation capacity in 3D environment. To show this process a contribution is prepared, which summarises the history of achievements in pre-diction of behaviour of structural connections. The validation on an example of an unstiffened haunch in a welded portal frame joint and verification on the column web panel and a column stiffener is shown

2:45 pm - 3:00 pm

Experimental investigation on the instability phenomenon in stainless steel connections – Plate Curling

Sobrinho, Kelvin[1]; Tenchini, André[2]; Henriques, Jose[3]; Cordeiro, Monique[2]; Vellasco, Pedro[2]; Lima, Luciano[2]
[1]GECIV – Post-Graduate Program in Civil Engineering, UERJ - State University of Rio de Janeiro, Brazil; [2]Structural Engineering Department, UERJ – State University of Rio de Janeiro, Brazil; [3]CERG – Construction Engineering Research Group, Faculty of Engineering Technology, University Hasselt, Belgium
Keywords: Stainless steel, Bolted Connections, Experimental Tests, Plate Curling

Bolted joints with thin plates under uniaxial tension are subject to the occurrence of the phenomenon known as curling effect, which is able to influence the connection behavior and decrease its ultimate strength. For stainless steel joints, the mechanism is even more important, because it is a material with high deformation capacity. Current standards and codes not consider a real deformation capacity that this type of material possess, and the equations used for limit state design are applied in analogies to carbon steels that have a very distinct behavior, thus becoming not at all economical. In this paper is an experimental study of the bolted joints of stainless steel of both austenitic 304 and ferritic 430 types with one and two cut planes. In order to evaluate the influence of the curling effect on the ultimate strength of the bond,

tests were carried out with stiffened plates, preventing this effect, and their results are compared with models in which the curling effect occurs with one and two cuts planes in the bolts. The final load values found experimentally are compared to the values of Eurocode 3 (part 1.4), American standard (ASCE 8-02) and Australian / New Zealand standard (AS / NZS 4673).

3:00 pm - 3:15 pm

Ductility Assessment of Structural Steel and Composite Joints

Jaspart, Jean-Pierre; Corman, Adrien; Demonceau, Jean-Francois
Liege University, Belgium
Keywords: Joint, experimental test, ductility, rotation capacity

Eurocode 3, in its Part 1-8, and Eurocode 4 provide designers with assessment procedures for the initial rotational stiffness and the resistance of steel and composite joints respectively. These design procedures refer to the so-called component approach and have been validated through numerous comparisons with test results and numerical non-linear simulations.

For beam and column members, the resistance level considered by the code is the one which could not be exceeded at ULS and it depends on the cross-section class (Class 1 to Class 4). For Class 1 cross-sections, the plastic resistance may be considered and internal rotations may take place and develop in the cross-section in the case ductility criteria are met. If plastic rotation capacity is available, a plastic global analysis of the structure may be contemplated.

For connections and joints, a similar concept is to be applied, but unfortunately very few information is provided in the Eurocodes which would enable the designer to check whether enough plastic rotational capacity is locally available.

In this paper, a procedure to estimate the rotation capacity of joints is presented. As for the evaluation of the stiffness and resistance properties, it refers to the component method approach. Its validity is demonstrated through comparisons with experimental data.

3:15 pm - 3:30 pm
Keywords: Column base joints, experiment, analytical model, bending

Behaviour of column base plates under bi-axial bending moment

Seco, Laura[1]; Couchaux, Maël[1]; Hjiaj, Mohammed[1]; Neves, Luís[2]
[1]Institut National des Sciences Appliquées de Rennes, France; [2]University of Coimbra, Portugal
Keywords: Column base joints, experiment, analytical model, bending

Base plates of corner columns in buildings are usually subjected to biaxial bending moment combined with axial force. This combination of forces is not covered by most of the existing design methods and particularly of the component method adopted in Eurocode 3 Part 1-8 that treats exclusively the case of a bending moment about the major (strong) axis combined with an axial force

This paper deals with a full scale experimental test program of six column bases subjected to bi-axial bending moment, focusing on the influence of the thickness of the base plates and bending loading conditions on the overall behavior. The presented results are expected to be useful for the validation of analytical models for the resistance, initial stiffness and rotational capacity calculation to be developed in the future.

Members 2: Beams

Time: Wednesday, 11/Sep/2019: 1:45 pm - 3:30 pm · Location: C202
Session Chair: Harald Unterweger, Graz University of Technology
Session Chair: Jurgen Becque, The University of Sheffield

1:45 pm - 2:00 pm

Elastic Buckling Strength of H-shaped Beams Subjected to End Moment and Uniformly Distributed Load

Shinohara, Daiki; Ikarashi, Kikuo
Tokyo Institute of Technology, Japan
Keywords: H-shaped beam, Lateral buckling, Local buckling, Uniformly distributed load, Energy method

Important factors in evaluating lateral buckling strength of H-shaped steel beams are the boundary conditions and the moment ratio at the ends of beams. The influence of the moment ratio on lateral buckling strength is generally evaluated using the moment gradient correction factor, and a lot of researchers studied on this. However, because the boundary and stress conditions considered in these studies are insufficient, the proposed evaluation formulae are not highly accurate. Therefore, purpose of this paper is to propose more accurate approximation formulae of the moment gradient correction factor for use as design formulae. Authors first calculate elastic lateral buckling strength when bending moment and uniformly distributed load act on the beams in various boundary conditions by theoretical analysis based on energy method. And, based on this, this paper proposes the approximation formulae. This paper also considers not only lateral buckling strength but also local buckling strength by conducting theoretical analysis.

The approximation formulae of the moment gradient correction factor related to lateral buckling strength were developed from the past studies. And, they use indices including the influence of the cross sectional shape and the position where uniformly distributed load acts. Regarding local buckling, theoretical analysis based on the energy method was carried out. As a result, there are three results mainly from this study that: 1) Approximation formulae of the moment gradient correction factor were proposed under various boundary conditions. 2) Lateral buckling strength is particularly affected by the position where the equally distributed load acts. 3) Effects of the moment ratio in local buckling strength are small compared to the case of lateral buckling.

2:00 pm - 2:15 pm

Local Buckling Strength of Vertical Haunch H-Shaped Beam Under Shear Bending

Ishida, Wataru; Ikarashi, Kikuo
Tokyo Institute of Technology, Japan
Keywords: Vertical Haunch H-Shaped Beam, Elastic Buckling, Local Buckling, Stress Distribution, Finite Element Method

Vertical haunch H-shaped beams have been designed in steel structures from the viewpoints of economic reasons, required strength of joints, and connection of beams with different depth. However, there are few studies on the mechanism and the strength of the elastic local buckling of vertical haunch H-shaped steel beam. The influence of taper gradient and haunch length on local buckling of web and flanges have not been clarified.

The purpose of this paper is to propose an elastic local buckling strength evaluation method of vertical haunch H-shaped beam using theoretical analysis and finite element method. As a prerequisite for the buckling analysis, stress distribution of each plate element is revealed in consideration of geometrical characteristic of tapered form. The validity of the stress distribution is confirmed from the finite element analysis.

We perform elastic buckling analysis using the finite element method. From the results, it was clarified that the beam behaves differently depending on the cross-sectional shape and length of the equal cross-sectional beam. We classify the mode of local buckling and show the elastic buckling strength evaluation method.

2:15 pm - 2:30 pm

Buckling of web-tapered high strength steel beams

Wang, Yixin; Bradford, Mark Andrew
UNSW Sydney, Australia
Keywords: HSS, non-prismatic, buckling, direct strength method

High strength steel (HSS) is seen as a viable alternative to mild steel, because when strength rather than stiffness governs the design, less of it is needed. Further weight minimisation advantages may be gained by tapering the web of an I-section profile to best suit the bending moment and shear force distribution in a beam. Optimal HSS members have much more slender plate elements than their mild steel counterparts, and this may result in a greater propensity for local and global buckling to interact. The additional effect of the non-prismatic nature of a tapered beam need also to be considered in design. A numerical study is presented of the buckling of tapered beams under moment gradient, in which the non-linearities associated with the steel (stress-strain and residual stresses) and tapering are included. The study concludes by presenting a design proposal in analytical form based on an extended parametric study.

2:30 pm - 2:45 pm

Lateral torsional buckling of hybrid steel-glass beam

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Faculty of Civil Engineering, CTU in Prague, Czech Republic
Keywords: glass, hybrid beam, adhesive bonding, stability, imperfection, numerical model

In modern architecture, the importance of glass is growing, as emphasis is placed on the transparency and lightness of the structures. Therefore, glass is not used only as a filling material for windows but it is also increasingly used for load-bearing structural elements, which carry, in addition to their own weight, loads of wind, snow or imposed load. Glass is a material with high compressive strength but low tensile strength. It behaves flexibly until it breaks with brittle fracture, which occurs suddenly without prior warning. This must be taken into account when installing, operating and designing structural glass elements, details especially. Thus, the safe design of these structural elements requires a different approach. The structures should have not only sufficient load-bearing capacity, i.e. first crack in the glass pane, but they should also be able to carry the load after the failure. This residual load-bearing capacity of the glass beam can be increased by adding other material such as steel, stainless steel, wood or concrete.

Research carried out at the Faculty of Civil Engineering of the CTU in Prague was focused on hybrid beams consisting of glass webs and steel flanges with adhesive bonding between the steel and glass. The combination of these two materials permits to utilize the strength and ductility of the steel and to keep up the transparency and esthetic appearance. Hybrid beams can be installed vertically and horizontally and therefore they can be used as façade fins or as members of high transparent roof or floor structure. If hybrid beams are used as vertical beams supporting glass facades, consideration should be given to the loss of lateral and torsional stability that may occur in the load case of the wind suction.

2:45 pm - 3:00 pm

Imperfection sensitivity of corrugated web girders subjected to lateral-torsional buckling

Jáger, Bence[1]; Kachichian, Mansour[1]; Égető, Csaba[2]; Dunai, László[1]
[1]Department of Structural Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Hungary; [2]Department of Structural Engineering, Faculty of Civil Engineering, Budapest University of Technology and Economics, Hungary
Keywords: corrugated web, lateral-torsional buckling, bending, trapezoidal web

Current standards and specifications do not provide prescriptions how to determine the lateral-torsional buckling (LTB) strength of trapezoidally corrugated web girders. In the literature some research work can be found on the investigation of the LTB behavior mainly by FE analysis, and on the derivation of possible analytical solutions for the resistance. The number of available experimental results is limited in the literature therefore the authors performed an extensive test program on eleven full-scale test specimens in laboratory conditions. Based on the experimental test results an advanced FE model is developed. Standards provide equivalent geometric imperfections including initial geometric imperfections and residual stresses for structural members. These proposals have not been, however, investigated for the application to trapezoidally corrugated web girders. Thus in this study an imperfection sensitivity analysis is performed and a proposal is developed for the equivalent geometric imperfections to be applied in FEM based design.

3:00 pm - 3:15 pm

Lateral-torsional buckling of stainless steel beams with slender cross section

Šorf, Marek; Jandera, Michal
Czech Technical University in Prague, Czech Republic
Keywords: lateral torsional buckling, local buckling, stainless steel, beam

The contribution shows experimental and numerical research of welded slender stainless steel I-section beams. Difference in behavior of stainless steel and common carbon steel members is generally known, but design of stainless steel members has been established mainly for hollow sections (CHS, SHS/RHS) as these are the typical stainless steel profiles. Currently, open sections are also being used in structures and the design rules for both local buckling of very slender sections as well as lateral torsional buckling reduction factors are based on very limited experimental and numerical research. For this reason new research covering these phenomena was started at the Czech Technical University in Prague. A numerical model was used for design of test arrangement, the geometrically and materially nonlinear analysis with imperfection was made in software Abaqus. The experimental program consisted of six stainless steel beam tests being used for a model validation. The tests employed two stainless steel materials (austenitic and ferritic steel), one

section slenderness (Class 4 for web and flange) and three beam slenderness. A parametric study based on the validated numerical model will be used to compare existing design procedures and their possible refinement for Class 4 sections.

3:15 pm - 3:30 pm

Effect of Stiffener Position on Buckling Behavior of H-Shaped Steel Beam with Upper Flange Restraint

Igawa, Naoki; Ikarashi, Kikuo
Tokyo Institute of Technology, Japan
Keywords: transverse stiffener, H-shaped beam, lateral buckling, plate local buckling, FEM analysis

The upper flange of the H-shaped steel beam is usually restrained by a concrete slab. Torsional rigidity at the upper flange is increased due to the restraint of the upper flange, and in the usual case, the lateral buckling mode changes to a lateral buckling mode with distortion of the cross section. It is well known that this restraining effect greatly increases the elastic lateral buckling strength of the beam. In recent years, evaluation methods of buckling strength and plastic deformation capacity of these beams are being established.

When the transverse stiffener is placed on the H-shaped beam restrained by the upper flange, the distortion of the beam cross section is restricted. This effect improves the lateral buckling strength and the plastic deformation capacity of the beam. However, the relationship between the stiffener position and buckling behavior is not clear. And also the effective stiffener position is not clear.

In this study, effective stiffeners positions were examined using the finite element method for H-section beams with various cross sections and length, and the scope of their application was clarified. The beam section is H-shaped and the upper flange is completely constrained. Targeted buckling mode is lateral buckling and local plate buckling.

In conclusion, when the H-shaped beam restrained by the upper flange is laterally buckled, the effective position of the stiffener can be expressed by using a new index "Ts" representing the rate of increase of the elastic lateral buckling strength. If local plate buckling occurs, the effective stiffener position can be expressed as the distance from the beam end. Also, the distance is the same as for the beam without the upper flange restraint.

CFS2: Cold formed steel, sandwich pannels

Time: Wednesday, 11/Sep/2019: 4:00 pm - 5:30 pm · Location: C204
Session Chair: Thomas Misiek, Breinlinger Ingenieure
Session Chair: Nikolaj Rangelov, UACEG Sofia

4:00 pm - 4:15 pm

Experimental investigation of flexural buckling of sandwich panels with steel facings

Balázs, Ivan; Melcher, Jindřich
Brno University of Technology, Faculty of Civil Engineering, Czech Republic
Keywords: Buckling, experiment, sandwich panel, stability, steel

Sandwich panels are widely used in building industry particularly as members of roof and wall cladding. Although they primarily resist transversal loads, axial forces may arise e.g. due to stabilizing function of panels that may prevent buckling of supporting members of steel load-bearing structure and transfer the stabilizing forces. The paper focuses on problem of flexural buckling of sandwich panels with thin steel facings. The problem of stability of axially loaded sandwich panels is outlined. To verify the actual behaviour of sandwich panels under axial load, a series of full-scale tests of flexural buckling of selected type of sandwich panels with thin steel facings and soft core was performed. Continuous measurement of axial load, deflection of the panels and strain on both facings was performed during each test. Evaluation of the test results was performed using Southwell plot and statistical methods. The paper presents the utilized test setup, procedure of testing, failure modes and summarizes selected results of the tests. The findings obtained from the tests are discussed. The results will be compared with results of numerical investigation of the problem and with calculations according to the theory of stability of sandwich structures.

4:15 pm - 4:30 pm

Experimental investigation of stability behaviour of members supported by sandwich panels at elevated temperature

Lendvai, Anita; Joó, Attila László
Budapest University of Technology and Economics, Hungary
Keywords: sandwich panels, stability behaviour, elevated temperature, experimental test, stiffening effect

The paper introduces experimental tests in order to examine the stability behaviour of members supported by sandwich panels at elevated temperature.

The overall dimensions of test specimens are 3.0 m x 3.0 m sized diaphragms, where the spacing of the 3 hot rolled columns is 1.5 m, and on the outer face of columns sandwich panels are installed. The loading protocol after reaching elevated temperature was monotonically increasing axial force acting on middle column until the failure of member. Elevated temperature on the sandwich panels was reached by ceramic heating pads.

Total of 18 different test configurations were performed, in which the type of the cladding (mineral wool or PIR core), thickness of the cladding (100, 160 or 230 mm), and the temperature (20, 400, 600 °C) were varied.

The experimental research programme was executed as part of RFCS project STABFI. The principal aim of the project is to prove that the sandwich panel's stiffening effect is non-negligible at elevated temperature. Further aims are to (i) determine main failure modes, (ii) find those variables, which have primary effect on the resistance of the structure, and (iii) to get data at different temperatures for further numerical modelling.

4:30 pm - 4:45 pm

Shear behaviour of sandwich panel fasteners in fire

Arha, Tesfamariam; Cábová, Kamila; Lišková, Nikola; Wald, František
Czech Technical University in Prague, Czech Republic
Keywords: steel structures, stabilization, fire design, sandwich panels, connection, shear resistance, stress skin design

In recent years the usage of sandwich panels as wall cladding and roofing has increased significantly. It has been shown that by using sandwich panels and trapezoidal sheeting as a stabilizing members, a considerable amount of savings of steel can be achieved for structural members at ambient temperature. Previous researchers has not covered this topic under elevated temperature and these stabilising effects may also help to achieve similar savings in case of fire. The behaviour of sandwich panel stiffeners in fire is very important in order to predict and investigate the whole structure. Therefore, an experimental investigation was conducted to study the shear behaviour of sandwich panel joints in fire when loaded in shear under the diaphragm action. In this paper the experimental results of 16 sandwich panel fastener tests are presented which are carried out under the RFCS re-search project STABFI which is performing a research currently on the stabilization of a structural building using the cladding systems in fire. The results of the tests show that bearing failure of the inner steel sheet was the main failure mode. There was no failure of screws for all the tests at ambient and elevated temperatures except one. The results of the tests provided experimental data for the sandwich fasteners related to building stabilization in fire through the cladding systems which is under investigation of RFCS project STABFI.

4:45 pm - 5:00 pm

Numerical modelling of a two storey LWS building braced with gypsum-based panels

Shakeel, Sarmad; Campiche, Alessia; Landolfo, Raffaele
University of Naples "Federico II", Italy
Keywords: Gypsum-sheathed CFS structures, seismic response, shake-table tests, non-linear building modelling

The seismic behaviour of a full-scale two-storey Cold-Formed Steel (CFS) building is explored via the shake-table tests on its bare structure and the complete construction phases. Starting from the shake-table test results, advanced numerical models have been developed using the OpenSees software, which also consider both the structural and the non-structural elements along with the contribution offered by the finishing components to the lateral force resistance. Numerical models implemented for both construction phases are able to simulate with good accuracy the experimental seismic behaviour of the building, in term of its fundamental period, the drift peaks and the displacement time history.

5:50 pm - 5:15 pm

Quantifying the seismic ductility of lightweight steel lateral force resisting systems through procedures of FEMA P695

Shakeel, Sarmad
University of Naples "Federico II", Italy
Keywords: Cold-formed steel, Shear walls, Gypsum board sheathing, Strap braced stud walls, Incremental Dynamic Analysis, Behaviour factor, FEMA P695

Seismic design regulations rely on certain factors to reduce the earthquake actions due to inherent ductility and overstrength of the lateral force resisting systems. The behavior factors given in Eurocodes are one such example, which when applied during the design process will ensure the life safety performance level of a building. Lightweight steel (LWS) structures fabricated with Cold formed steel (CFS) profiles have now been in use for quite a sometime in earthquake prone European regions, however the current in practice edition of Eurocodes fail to acknowledges their seismic performance by does not providing behavior factors for them. The study presented herein addresses this issue by evaluating behavior factor for the two most commonly used LWS systems: CFS strap braced studs walls and CFS shear walls with gypsum board sheathing through FEMA P695 methodology. For each type of system, a set of archetypes, which represent a range of design parameters and building configurations are designed following the capacity design approach and their response is idealized by nonlinear models. The performance of archetype models is evaluated systematically through the static pushover and the incremental dynamic analysis under a suite of forty-four normalized and scaled earthquake records, representing the probable seismic hazard to the buildings. Finally, by calculating the collapse probability while also considering the uncertainties from various sources, the suitability of trial value of behavior factor used in the design phase of archetypes is evaluated. Based on the results, it is concluded that a behavior factor of 2.5 and 2.0 for CFS strap braced stud walls and CFS shear walls with gypsum board sheathing is appropriate.

Connections 3: Connections, welds

Time: Wednesday, 11/Sep/2019: 4:00 pm - 5:30 pm · Location: C206
Session Chair: Aurel Stratan, Politehnica University of Timisoara
Session Chair: Eduardo de Miranda Batista, Federal University of Rio de Janeiro

4:00 pm - 4:15 pm

U-shaped steel plate dissipative connection for concentrically braced frames

Henriques, José[1]; Calado, Luís[2]; Castiglioni, Carlo[3]; Degée, Hervé[1]
[1]CERG – Construction Engineering Research Group, Faculty of Engineering Technology, University Hasselt, Belgium; [2]Instituto Superior Técnico, Universidade de Lisboa, Portugal; [3]Dept. of Architecture, Built environment and Construction engineering, Politecnico di Milano, Italy
Keywords: U-Shape Steel Plate, Dissipative Connection, Concentrically Braced Frame, Deformation Capacity, Fatigue

In concentrically braced frames, the use of dissipative connections allows to efficiently dissipate the seismic energy in earthquake scenarios and subsequently, to reduce the costs in the rehabilitation of the structure. To this end, U-shaped steel plates are simple and efficient connection components where significant dissipation of seismic energy can take place through the inelastic flexural deformation of the plate. This paper presents experimental results on the isolated U-shape steel plate connections and on single-storey concentrically braced frame (real scale) including the U-shape steel plate to connect braces to adjacent members. The executed tests considered both monotonic and cyclic loading. The results highlight the efficiency of the U-shape steel plate to dissipate the energy input through inelastic deformations. On the other hand, the cyclic tests show potential fatigue behaviour, as the deformation capacity is significantly reduced with repeated loading and increasing stress amplitude, requiring thus specific attention in practical design situations.

4:15 pm - 4:30 pm

Warping transfer superelement model for bolted endplate connections subject to 3D loads

Vaszilievits-Sömjén, Bálint[1]; Szalai, József[2]; Movahedi Rad, Majid[3]
[1]KÉSZ Holding Zrt, Hungary; [2]ConSteel Solutions Kft, Hungary; [3]Széchenyi István University, Győr, Hungary
Keywords: Warping, Joint, Component method, 3D loads

A simple beam element based modelling technique has been developed which makes possible to analyze frames with column-rafter bolted endplate connections, subject to 3D loads, compatible with the thin walled beam theory with 7DOF beam elements. The model previously developed by the same team for welded connections has been extended by the addition of linear spring elements to model the bolts located at the upper and lower beam flange level.

The spring stiffnesses are calculated based on the extension of the Eurocode component method and verified by simulations performed with FEA software IDEA StatiCa and Abaqus. The model predicted results are compared with results of full-scale laboratory test.

The method can be used to for realistic elastic first and second order analysis, linear buckling analysis of such plane structures with moment bearing bolted connections, where the out-of-plane effects cannot be disregarded and their contribution to the final behavior of the structure is important. Analysis speed compared to other solutions is very efficient due to the use of analytic corner description with compatible 7DOF thin-walled beam elements.

4:30 pm - 4:45 pm

Experimental study on SCFs of empty SHS-SHS T-joints subjected to static out-of-plane bending

Matti, Feleb N.; Mashiri, Fidelis R.
Western Sydney University, Australia
Keywords: Stress Concentration Factors, Square Hollow Sections, Empty T-Joints, Experimental Study

This paper presents an experimental study on stress concentration factors (SCFs) of empty (unfilled) square hollow section (SHS) T-joints specimens. Square hollow sections are extensively used for the columns and truss of numerous structures such buildings, bridges, cranes, glass houses and towers. However, there is limited investigation on SCFs of empty SHS-SHS T-joints under static out-of-plane bending loads which needs to be explored. As a result, there are no design guidelines for empty SHS-SHS T-joints under out-of-plane bending. To fulfill this research gap in the literature and develop the fatigue design rules of thin-walled SHS T-joints, four empty SHS-SHS T-joints were tested under static out-of-plane bending loads on the brace. The four empty T-joints are made up of empty SHS brace and empty SHS chord members. The non-dimensional parameters of the SHS-SHS T-joints are Beta, 2Gamma and Tau. The range of each non-dimensional parameter of the SHS-SHS T-joint specimens used in this investigation are $0.25 \leq Beta \leq 1$, $25 \leq 2Gamma \leq 33.33$ and $0.75 \leq Tau \leq 1$. The distribution of the SCFs and the peak SCF at the hot spot locations (line A, B, C, D and E) of empty T-joints were determined by attaching strain gauges on the T-joint specimens. In summary, the maximum SCFs of the four SHS-SHS T-joints under out-of-plane bending commonly occurred along line B and C.

4:45 pm - 5:00 pm

Analysis of Mechanical Properties of Cold-Formed High Strength Steels at the Weld Area

Dolejš, Jakub; Werunský, Martin
CTU in Prague, Czech Republic
Keywords: high strength steel, cold-formed member, welding, connection, FEM

Nowadays, steels with yield strength higher than 550 MPa and ultimate strength higher than 700 MPa are considered as high-strength steels. Their utilization allows to construct structures with lower dead weight and with higher load capacity. Objective of author´ s research is S960 steel, which is presumed to be utilized in civil engineering in future. Construction practice faces a number of difficulties when using high-strength steels. One of them is the limited knowledge of material properties in cold-formed areas, in addition to the welding process. The aim of the started research is to describe altered mechanical properties (strength, ductility, toughness and hardness) of the S960 grade steel in the cold-formed area after 90° bending and welded by the MAG with the filler material of the same class. The change in mechanical properties will be studied depending on the bending radius and sheet thickness ratio, the strength of consumable and also the temperature of the preheating. Data obtained from hardness experiments and tensile tests will be used to validate and verify the model created in the advanced FEM program. Consequently, an extensive parametric study is planned.

5:00 pm - 5:15 pm

Welds on high-strength steels – Influence of the welding process and the number of layers

Stroetmann, Richard; Kästner, Thoralf
Technical University of Dresden, Germany
Keywords: high-strength steels; welding; connection

The application of high-strength steels provides in many types of constructions due to the resource-conserving use of material economic and ecological advantages. However, for welded constructions some of these advantages are partially offset due to less favorable design rules and more complicated processing regulations. Weaknesses in the systematic of determining the resistance of welds by Eurocode 3 parts 1-8 and 1-12 are the reason, that the dependencies of the base and the filler material, the welding process, the type of stress and the construction form are summarized in the correlation factor βw.

Aim of the ongoing AiF-FOSTA research project P1020 is the development of fundamentals, which lead to significant improvements of design and execution rules for weldings in structures made out of high strength steels. The development of design rules follows the objective of a more simple and economic execution. The possibility of undermatching welds, the construction form of the joints and the type of stresses will be considered in a convenient

way. Input data of the resistance are the tensile strength and ductility of the welds itself as well as the construction related requirements on ductility.

As part of the development of the new design approach, the influence of the welding process and the number of weld layers was examined. Hereby, the load-bearing characteristics of fully mechanized welds was compared to manual produced welds. Furthermore, the influence of different number of weld layers was examined considering two filler-metals. These examinations include tensile tests and hardness measurements in two different levels of the weld. The intended contribution gives an overview of the experimental test results.

5:15 pm - 5:30 pm

Stainless steel fillet weld tests

Feber, Nina; Jandera, Michal; Forejtová, Lucie; Kolařík, Ladislav
ČVUT, Czech Republic
Keywords: correlation factor, stainless, fillet welds

The correlation factor for determining the design resistance of fillet welds should be taken as 1,0 for all stainless steel families according to Eurocode 3. The aim of this study was to investigate the value of the correlation factor for austenitic grade EN 1.4301, based on experiments. This article describes 5 uniaxial tests of stainless steel weld connections. The specimen contains two plates of 15 mm thickness connected by four longitudinal fillet welds. The tests were performed with the load parallel to the weld causing only shear stress in the fillet weld. Every specimen was tested to investigate the strength, strain and failure mode. During the tests, for some specimens, deformations were measured using digital image correlation technique (DIC) to obtain the strain field around the welds and displacement between the plates.

Members 3: Beams, beam-columns

Time: Wednesday, 11/Sep/2019: 4:00 pm - 5:30 pm · Location: C202
Session Chair: Ryoichi Kanno, Nippon Steel Corporation
Session Chair: Donald White, Georgia Tech

4:00 pm - 4:15 pm

The use of inclinometers and DIC to measure the rotation in full-scale tests on construction elements

Lauwens, Kathleen[1,2]; Fortan, Maarten[1,2]; De Weerdt, Jurre[3]; Pelgrims, Patrick[3]; Rossi, Barbara[1,4]
[1]KU Leuven, Department of Civil Engineering, Belgium; [2]Research Foundation Flanders, Belgium; [3]Thomas More, Sint-Katelijne-Waver, Belgium; [4]University of Oxford, Department of Engineering Science, Oxford, UK
Keywords: torsion test, DIC, inclinometer, beam, stainless steel

As part of a study into the torsional behaviour of stainless steel beams, a relatively small device has been developed to accurately measure the 3D rotation over the full 360° range. This device is an accelerometer based tilt sensor, or inclinometer, which enables the user to obtain real-time rotations. Together with these inclinometers, the innovative technique Digital Image Correlation (DIC) can be applied in order to combine the advantages of both systems. This paper describes the development of these inclinometers and the application of Digital Image Correlation to extract rotations.

4:15 pm - 4:30 pm

Stainless steel SHS and RHS beam-columns

Židlický, Břetislav; Jandera, Michal
CTU in Prague, Czech Republic
Keywords: Stainless steel, Slender member, Beam-column, Interaction factor

Presented research deals with stainless steel square hollow and rectangular hollow section (SHS and RHS) slender members loaded by bending moment and compressive force. Four tests of eccentrically loaded stainless steel pin-ended columns were conducted. Data obtained from the experiments were used for the numerical model validation. A comprehensive numerical parametric study was made in finite element software Abaqus using geometrically and materially non-linear analysis with imperfection (GMNIA). All three main stainless steel groups were considered in study, namely austenitic, ferritic and duplex. The investigated parameters were mainly section slenderness, member slenderness and ratio between compressive force and bending moment. Only uniform bending moment along the member length was considered. Based on the numerical parametric study results a new design approach for stainless steel SHS and RHS beam-columns has been derived. It is described and evaluated in this paper together with recently published design procedure developed by Ou Zhao.

4:30 pm - 4:45 pm

Experimental Study on Square Steel Tubular Columns under Compressive Force with Biaxial Bending Moment

Sato, Atsushi; Onogi, Takeshi
Nagoya Institute of Technology, Japan
Keywords: Square steel tubular column, Axial force ratio, Slenderness ratio, Biaxial bending, Maximum bending moment, Plastic deformation capacity

Horizontal force in arbitrary direction subjects to the space moment resisting frame will be essentially resisted by the flexural manner of the columns. As a result, biaxial moment and axial force are applied to the columns. The Architectural Institute of Japan (AIJ) has a publication that can be used to design the column under compressive axial force and biaxial bending. However, the design rule which is used to design the column in combined loading condition is not shown clearly with the sufficient test data. Moreover, the column which can guarantee the full plastic moment under the combined loading condition is not shown explicitly.

In this paper, tubular hollow square steel columns are studied by the full-scale testing to verify the ultimate strength and plastic deformation capacity. The parameters selected for testing are the direction of bending moment, the compressive axial force, and the slenderness ratio. From the test results, local buckling at the plate elements was observed in the specimens where the applied to axial force was relatively small. However, compared with the results from the uniaxial bending moment where the bending moment was applied the principal axis, it was found that the column under 45 degrees loading direction was not sensitive to the local buckling due to the stress distribution in the plate elements. On the other hand, the columns where second-order effects determined the maximum strength were not influenced by the loading direction. Finally, it was found that the formula recommended by AIJ can guarantee sufficient strength and plastic deformation capacity, although the design rule in the recommendation provided overly conservative results.

4:45 pm - 5:00 pm

Design Limitations for the Steel Beam-Column to Ensure Full Plastic Moment

Sato, Atsushi[1]; Aoyama, Masahiro[1]; Inden, Kenta[1]; Mitsui, Kazuya[2]; Ono, Tetsuro[1]

[1]Nagoya Institute of Technology, Japan; [2]Nippon Steel and Sumitomo Metal Co.

Keywords: steel beam-column; combined loading; second-order effect; full plastic moment, in-plane behaviour

The moment resisting frame system that is composed of beams and columns will resist the horizontal loads by the flexural manner of the columns. Under the seismic load action, the horizontal force will be significant, and the column shall resist axial force and a significant amount of shear force. Therefore, the column is under the combined loading condition (so-called beam-column). In the Ultimate Limit State (ULS), the inelastic behaviour of the members are used in the design; strong column-weak beam philosophy is used to prevent the collapse of the structural system. Column Overstrength Factor (COF) is checked between the capacity of the connected beams and columns, and the full plastic moment is used. The full plastic moment of the column is computed including the effect of axial force. Therefore, it is crucial to guaranty that the column can resist the full plastic moment at the face of the beam-to-column connection. The structural performance of the beam-column will be affected by the axial force level, and second-order effects introduced by the deflection of the member can be dominant in a relatively slender column. The design recommendation for the column existing in Japan does not show the limitations that can be used to avoid the second-order effects in the ULS.

In this paper, the second-order effect introduced by compressive axial force to the column is studied. Numerical simulation is used to clarify this issue, and in-plane behaviour is evaluated. Parameters selected for the analysis are cross-section shape, slenderness ratio, compressive axial force, bending moment distribution, material strength, and initial imperfection. From the results, it was found that material strength is not a significant parameter for the second-order effects. Finally, the formula which can ensure the full plastic moment of the column at the face of the beam-to-column connection was proposed. Proposed formula was composed by the information of cross-section shape, slenderness ratio, bending moment distribution, and axial force level subjected to the column.

5:00 pm - 5:15 pm

Study on the deformation and rotation capacity of HSS beams and beam-columns

Müller, Andreas; Taras, Andreas
Bundeswehr University Munich, Germany
Keywords: deformation capacity, cross-section classification, high-strength steel, design by analysis

With increasing use of high-strength steel grades, the need for more accurate design specifications arises, with the aim of fully exploiting the material benefits and create economic advantages. Ac-cording to Eurocode 3, the maximum rotational capacity is limited and linked to the definition of cross-sectional classes. For class 1, the rotation θ is assumed to be "infinite", while it drops significantly for class 2 and 3 to a maximum rotation capacity of θpl and θel, respectively. In reality, in spite of their lower hardening capacity and ultimate strains, high-strength steel sections display a non-negligible rotational capacity that exceeds these code predictions, which were developed for mild steel and with a level of analysis in mind that is suitable for hand calculations. For an increased use of high-strength steel sections, it is thus very important to understand and to be able to predict a more realistic deformation and rotation capacity, with the aim of implementing the findings in tools for advanced, FEM-based Design by Analysis (DbA) approaches. As an initial step in this direction, the proposed paper shows the results from numerical calculations on the rotational capacity of HSS rectangular hollow sections. The numerical results are calibrated against laboratory tests. Consequently, different rectangular cross section dimensions but also variations of the steel grade and the thickness are chosen and calculated in the finite element program ABAQUS. As the rotational capacity is strongly dependent on the load scenarios, e.g. the applied normal forces, different N-M-Interactions are considered. Finally, a comparison with the existing code provisions in both Euro-code 3 and the seismic design rules of Eurocode 8 completes the study.

5:15 pm - 5:30 pm

The stability of semi-braced steel frames containing members with stepped segments

Ma, Terence; Xu, Lei
University of Waterloo, Canada
Keywords: Semi-braced steel frame, Storey-based stability, segment, Stepped Members, elevated temperature

A new method is presented for evaluating the stability of a semi-braced steel frame containing stepped members. Stepped members consist of multiple segments with differing sectional or material properties, such as the cross-sectional area, moment of inertia, or elastic modulus. For instance, steel members subjected to non-linear elevated temperature distributions contain longitudinally varying modulus of elasticity. The proposed method is in the form of a storey-based lateral stiffness equation for semi-rigidly connected members with up to three segments. A structural frame becomes laterally unstable when its lateral stiffness diminishes to zero. The efficiency of the proposed method is demonstrated via an example of a semi-braced steel frame containing stepped members, whereby the critical gravity load causing instability of the frame is computed. The results obtained in the example were also validated via finite element analysis.

K2: Keynote lectures

Time: Thursday, 12/Sep/2019: 8:30 am - 10:00 am · Location: B286
Session Chair: Esther Real, Universitat Politècnica de Catalunya
Session Chair: Josef Machacek, Czech Technical University in Prague

8:30 am - 9:00 am

Design by Advanced Analysis – 2016 AISC Specification

Ziemian, Ronald[1]; Wang, Yunfei[2]
[1]Bucknell University, Lewisburg, Pennsylvania, USA; [2]Cornell University, Ithaca, New York, USA
Keywords: structural stability; global analysis; AISC specification

At the heart of the provisions for assessing structural stability within the American Institute of Steel Construction's Specification for Structural Steel Buildings is the direct analysis method. The fundamental concept is that the more behavior that is explicitly modeled within the analysis, the simpler it is to define the Specification's design requirements. In other words, the direct analysis method consists of calculating strength demands and available strengths according to a range of well-defined and fairly detailed analysis requirements. This paper begins with an overview of two logical extensions to AISC's direct analysis method, both of which are now provided in the Specification's Appendix 1 – Design by Advanced Analysis. In establishing these approaches, many systems were investigated and it was found that systems with beam-columns subject to minor-axis bending appeared to deserve additional attention. This paper presents a detailed study that investigates such members.

9:00 am - 9:30 am

Stability design of steel structures: From members to plates and shells

Simões da Silva, Luís; Tankova, Trayana; Martins, João Pedro
ISISE, Department of Civil Engineering, University of Coimbra, Portugal
Keywords: buckling resistance, beam-column, reliability, local buckling, tapered member

This paper presents an overview of the current design procedures for the buckling design of members, plates and curved panels. It highlights recent developments in these fields, namely methodologies for the evaluation of the buckling resistance of generic beam-columns with variable cross section, loading and boundary conditions, the evaluation of the reliability of the Winter curve in slender webs and the development of design guidance for curved panels. Finally, the incorporation of some of these developments in the current revision of Eurocode 3 is discussed.

9:30 am - 10:00 am

Cold-formed high strength steel RHS under combined bending and web crippling

Li, Hai-Ting[1]; Young, Ben[2]
[1]The University of Hong Kong, Hong Kong (China); [2]The Hong Kong Polytechnic University, Hong Kong (China)
Keywords: high strength steel; web crippling; hollow section

This paper presents experimental and numerical investigations of cold-formed high strength steel (CFHSS) rectangular hollow sections (RHS) under combined bending and web crippling. In the experimental investigation, 5 pure bending tests and 28 combined bending and web crippling tests were conducted on RHS with measured 0.2% proof stress in the flat portion of the section ranged from 679 to 971 MPa. The combined bending and web crippling tests were performed using the Interior-One-Flange loading condition that specified in the North American Specification for cold-formed steel structures. The specimens were tested at various lengths to examine the interaction relationship between bending moment and concentrated interior bearing load. Finite element (FE) models were developed and validated against the test results for members under combined bending and web crippling as well as pure bending. Upon validation of the FE models, a parametric study was performed using the validated models to generate further numerical data over a wide range of web slenderness ratio, bearing length to web thickness ratio and bearing length to web flat portion ratio. The ultimate strengths obtained from experimental and numerical investigations were compared with nominal strengths calculated using the European Code. It is shown that the codified bending and web crippling interaction formula can be used for the CFHSS RHS members, while more accurate predictions can be achieved by using the recently proposed web crippling design rules.

Fire 1: Fire

Time: Thursday, 12/Sep/2019: 10:30 am - 12:15 pm · Location: C204
Session Chair: Nuno Lopes, University of Aveiro
Session Chair: Sheida Afshan, Southampton University

10:30 am - 10:45 am

Fire design of class 4 tapered steel beams with the General Method - a proposal

Maia, Élio; Couto, Carlos; Vila Real, Paulo; Lopes, Nuno
University of Aveiro, Portugal
Keywords: General Method, Tapered beams, Fire, Class 4, FEM

This paper describes the proposal and validation of the General Method for the out-of-plane stability of class 4 tapered beams at elevated temperatures.

The General Method (clause 6.3.4 of EN 1993-1-1) covers the safety check of structural elements with complex support conditions and/or of non-prismatic members. However, it's not widely validated at normal temperature and is inexistent in fire part of Eurocode 3 (EN 1993 1 2).

In a recent study, the authors have adapted current proposals/design methodologies at normal temperature to fire situation, namely the General Method, the DIN 18800-2 procedure and Marques et al.'s proposal. From it, the latter was deemed unsafe at elevated temperatures, while the DIN 18800-2 methodology was seen as unreliable in fire, given the high scatter of the results. Out of the three approaches, the adapted General Method was recommended for the safety-check of a tapered member in fire. Although safe, results have been found to be overly conservative (up to 35% on the safe side).

With the purpose of providing an accurate methodology for the safety check of tapered beams, improvements to the abovementioned modification of the General Method are proposed in the scope of this work.

The adaptation to fire was done by accounting for the reduction in steel material properties with the temperature, namely the reduction factors for the yield strength $k_{y,\theta}$ and for the Young's Modulus $k_{E,\theta}$. Also, the ultimate capacity of the members at elevated temperature was obtained numerically using shell finite elements for a geometrically and materially non-linear analysis with imperfections (GMNIA) in SAFIR.

From the improved correlation compared to the analytical adaptation using only the reduction factors $k_{y,\theta}$ and $k_{E,\theta}$, statistical evidence points towards the General Method producing accurate predictions of resistance for the out-of-plane stability of unrestrained tapered beams with class 4 cross-sections at elevated temperatures.

10:45 am - 11:00 am

Behaviour of slender plates in case of fire of different stainless steel grades

Arrais, Flávio; Lopes, Nuno; Vila Real, Paulo; Couto, Carlos
RISCO - Civil Engineering Department, University of Aveiro, Portugal
Keywords: stainless steel, fire, local buckling

The stainless steel has countless desirable characteristics for a structural material. Although initially more expensive than conventional carbon steel, stainless steel structures can be competitive because of their smaller or none need for thermal protection material and lower life-cycle cost, thus contributing to a more sustainable construction.

The austenitic stainless steels are generally the most used groups for structural applications but some interest has being recently shown for increasing the use of ferritic and austenitic-ferritic (Duplex) steels for structural purposes due to specific advantages. Some of those advantages are the very good resistance to wear and stress corrosion cracking of the duplex grade and the lower percentage of Nickel of the ferritic grade, which reduces its price.

Regarding structural fire resistance, in order to have a comprehensive understanding of the overall members resistance, it is important to first analyse the cross-section resistance, which is directly affected by local instabilities occurrence on the composed thin plates.

This work will present a numerical study on the behaviour of isolated plates at elevated temperatures, corresponded to the web (internal element) and flanges (outstand element) of I - cross sections, comparing the numerically obtained ultimate load bearing capacities with simplified calculation formulae for the application of the effective width method. Members composed of I-shape sections subjected to compression have both flanges and web in compression, whereas when the members are subjected to bending in the strong axis, a flange is in compression while the web is subjected to bending. Hence, outstand elements subjected to compression, internal elements subjected to compression and an internal elements subjected to bending will be numerically analysed, with the finite element method software SAFIR. As it is known that the different stainless steel grades of the austenitic, ferritic and duplex groups exhibit different strength retentions at elevated temperatures, the focus of this study will be on the influence of the stainless steel grade on the plates resistance predictions. Comparisons between the numerical results and the EC3 formulae for determining the efective area of thin plates will be also presented.

11:00 am - 11:15 am

Critical loads of semi-rigid columns subjected to non-linear temperature distributions

Ma, Terence; Xu, Lei
University of Waterloo, Canada
Keywords: Critical load, stability, nonlinear elevated temperature distribution, column out-of-plumbness, semi-rigid column

A numerical method is presented for calculating the critical load of a semi-rigidly connected column subjected to non-linear temperature distributions and applied gravity loads in fire. The modulus of elasticity in a column can vary longitudinally due to many factors, such as the presence of vertical gas temperature gradients in fires, localized heating and damage to insulation in fire. An analytical equation for calculating the critical load of a semi-rigidly connected column with up to three segments of varying temperatures in fire is presented. The assumption of semi-rigid connections in the proposed method is realistic and practical, but can be simplified to include the ideal cases of pinned and fixed connections. The effect of initial out-of-plumbness, which increases deflections under applied loads, on the inelastic behavior of columns is also considered. The proposed method is demonstrated via a brief numerical example and the results are verified via finite element analysis.

11:15 am - 11:30 am

Numerical investigation of thin-walled CFS columns in fire

Craveiro, Helder D.[1]; Henriques, José[2]; Santiago, Aldina[1]; Laím, Luis[1]
[1]ISISE – Institute for Sustainability and Innovation in Structural Engineering, Department of Civil Engineering, University of Coimbra, Portugal; [2]CERG – Construction Engineering Research Group, Faculty of Engineering Technology, University Hasselt, Belgium
Keywords: cold-formed steel, fire, buckling, finite element, thermal elongation

The structural performance of cold-formed steel compressed elements subjected to fire is investigated using finite element analysis. The numerical study is based on a set of experimental tests on cold-formed steel columns subjected to fire with restrained thermal elongation. On the fire resistance tests, different levels of restraint and load were considered. This allowed studying the influence of the generated internal forces during heating in the overall structural fire behaviour of the cold-formed steel columns. Specifically, in this study, two cross-section shapes are investigated, namely C-channels and Σ-channels (sigma).

Based on experimental results the numerical models were developed and calibrated using all mechanical and thermal properties determined experimentally at both ambient and elevated temperatures. In this paper the numerical modelling is detailed. Both heat transfer and mechanical models are presented. To further investigate the influence of some key parameters, such as initial applied load level, level of restraint to thermal elongation and slenderness,

a parametric study is presented. The obtained experimental and numerical results were compared with the currently available design guidelines in the EN 1993-1-2. The data collected from this parametric study will be used to develop/improve new/available design methodologies for cold-formed steel compressed elements in fire conditions with restrained thermal elongation. The level of restraint to thermal elongation will significantly influence the critical temperature of the cold-formed steel columns.

11:30 am - 11:45 am

Numerical modelling of cold formed steel members at elevated temperatures

Arrais, Flávio[1]; Lopes, Nuno[1]; Vila Real, Paulo[1]; Jandera, Michal[2]
[1]University of Aveiro, Portugal; [2]Czech Technical University in Prague, Czech Republic
Keywords: fire, purlin, cold formed steel

Steel structural elements composed of cold-formed thin-walled sections are becoming increasingly common in buildings due to their lightness and ability to support large spans. Cold-formed steel elements are typically used in steel structures, as purlins, joists, tracks, designed for different kinds of loads.

Due to their thin walls, there is a high susceptibility to the occurrence of different buckling phenomena, increased at high temperatures, such as local, global and distortional buckling. The thin walls of these profiles, along with the steel high thermal conductivity, provide a quick increase of temperature and consequently a great loss of strength and stiffness on these structural elements when subjected to fire.

The evaluation of the cold-formed steel elements resistance and behaviour through an experimental analysis is important on the design and parametric study of these profiles. However, due to the high costs associated to experimental tests the parametrization of the profiles behaviour has mainly been carried out through validated numerical studies.

Simply supported beams and columns are the focused elements analysed in the present research work. The validation of the numerical models is made against different experimental works performed by different authors.

Afterwards a parametric study is also presented through numerical analyses on the behaviour of simply supported elements, considering different initial imperfections, temperatures, cross-section slendernesses and steel grades.

In the finite element models, rectangular shell finite elements were used to reproduce local buckling phenomena due to the walls high slenderness. The numerical models were performed and analysed using geometrically and materially nonlinear analyses including imperfections (GMNIA) using the software SAFIR. Local and global buckling modes obtained in CAST3M were used to define the geometrical imperfection shapes.

11:45 am - 12:00 pm

Assessment of Eurocode Fire Design Rules for Structural Members Made of High Strength Steels

Couto, Carlos; Vila Real, Paulo
University of Aveiro, Portugal
Keywords: high strength steel, FEM, fire, Eurocode 3

The demand for structural members made of high strength steels (HSS) is increasing throughout the world. To reflect this, the future revision of Part 1-1 of the Eurocode 3 devoted to the design of steel structures, includes rules for steel with a yield strength up to 700 MPa. This decision must be accompanied by rules for the case of fire to avoid a gap in the design codes. The preparation of the next revision of Part 1-2 of Eurocode 3 is currently being undertaken within the scope of CEN, and the present paper aims at contributing to the definition of the current reliability level of existing design rules regarding their applicability to members made of HSS.

An extensive numerical investigation carried out with the Finite Element Method is performed following the usual GMNIA simulations at elevated temperatures. Remarks on the consideration of geometrical imperfections and residual stresses are given. The numerical tests allow the ultimate strength of structural members to be calculated and compared with the existing design rules. Finally, conclusions and recommendations are given based on this comparison.

12:00 pm - 12:15 pm

GBT-based semi-analytical solutions for the elastic/plastic stability analysis of stainless steel thin-walled columns exposed to fire

Gonçalves, Rodrigo de Moura[1]; Neves, Rui[1]; Camotim, Dinar[2]
[1]CERIS and Universidade NOVA de Lisboa, Portugal; [2]CERIS and Instituto Superior Técnico, Universidade de Lisboa, Portugal
Keywords: Stainless steel, fire, global buckling, local buckling, Generalized Beam Theory

Although initially more expensive than conventional carbon steel, stainless steel can be competitive because of its increased fire resistance, lower maintenance needs, higher corrosion resistance, better aesthetic appearance and lower life-cycle cost (SCI 2017). The fire behaviour of stainless steel members has been the subject of research of recent studies (Gardner & Baddoo 2006, Ng & Gardner 2007, Uppfeldt et al. 2008, Lopes et al. 2012). However, According to Eurocode 3, these members should be checked using the buckling interaction formulas for carbon steel members, which have been shown to be imprecise and even unsafe in some cases (Lopes et al. 2010). Moreover, studies concerning the behaviour of members with slender sections (Class 3 or 4 according to Eurocode 3), susceptible to local and/or distortional buckling, are still lacking.

To increase the knowledge on the behaviour of thin-walled stainless steel structures in case of fire, project "Fire design of stainless steel structural elements, StaSteFi" was launched in 2018. This paper reports the first activities carried out in the context of this project, which aimed at developing a fast and accurate tool to calculate elastic and plastic buckling (bifurcation) loads/modes of thin-walled stainless steel columns (uniformly compressed members) exposed to fire and undergoing global/local/distortional buckling. The tool is based on a semi-analytical approach that relies on Generalized Beam Theory, a thin-walled bar theory that efficiently accounts for cross-section arbitrary in-plane and out-of-plane (warping) deformation through the consideration of so-called "cross-section deformation modes" (see, e.g., Schardt 1989, Camotim et al. 2010). The intrinsic non-linear stress-strain law of stainless steel, including temperature effects, is taken into account using appropriate tangent elastic moduli, based on both J2 (von Mises) small-strain incremental and deformation plasticity theories. For illustrative purposes, the tool is applied to assess the elastic and plastic buckling behaviour of thin-walled lipped channel columns made with steel grade 1.403 and subjected to fire.

PI1: Plates

Time: Thursday, 12/Sep/2019: 10:30 am - 12:15 pm · Location: C206
Session Chair: Ronald Ziemian, Bucknell University
Session Chair: Eiki Yamaguchi, Kyushu Institute of Technology

10:30 am - 10:45 am

Solutions to simplified von Karman plate equations

Becque, Jurgen
The University of Sheffield, United Kingdom
Keywords: plates, post-buckling, Winter equation, von Karman equation

The post-buckling behaviour of elastic plates is described by the highly non-linear von Karman equations, which (with the exception of a few particular cases) are without a known solution. However, this paper demonstrates that, with the help of some simplifying assumptions which preserve the main mechanics of plate behaviour, the set of von Karman equations can be reduced to a single equation which only contains the vertical plate deflections as an unknown function and does not feature the Airy stress function. The equation is solved for the cases of a square uniaxially compressed plate simply supported along all sides, with the loaded edges forced to remain straight and with the unloaded edges either remaining straight or being free to pull in. It is shown that combining the resulting membrane stress distribution with von Karman's effective width concept leads to a Winter-type equation. The equation corresponding to an imperfection of b/200, where b is the plate width, agrees well with the current Winter design equation for steel plates.

10:45 am - 11:00 am

On the modal buckling of longitudinally stiffened plates

Adany, Sandor
Budapest University of Technology and Economics, Hungary
Keywords: longitudinally stiffened plates, buckling, modal decomposition

It is a usual engineering practice to apply stiffeners in thin plates to increase the resistance against plate buckling. In cold-formed steel structural members the buckling of longitudinal plate stiffener is typically called distortional buckling. In design codes for cold-formed steel members distortional buckling is clearly distinguished from local-plate buckling and from global buckling, and though the design methods are different in the various design codes, some reduction factor is calculated from the elastic critical load to each of the buckling types. In the case of welded plate girders longitudinal stiffeners are widely employed, too, but their buckling is unusual to describe as distortional buckling. A possible design approach, which is included in the relevant part of the Eurocode, is to interpret the stiffener buckling as a combination of plate-like behavior and column-like behavior, and therefore to calculate reduction factor by interpolating from reduction factors defined for plate-like and column-like behavior. In the actual paper the buckling of simple, longitudinally stiffened

plates is studied, however, by using the global-distortional-local classification. In the paper the linear elastic buckling behavior is discussed, by using the recently developed constraint finite element method, which can readily be applied for stiffened plates and can do modal decomposition, that is which can easily and objectively separate the global, distortional and local buckling. Examples for longitudinally stiffened plates with various geometries are given, subjected to various loading conditions.

11:00 am - 11:15 am

Modal analysis of thin-walled members with transverse plate elements using the constrained finite element method

Hoang, Trung; Adany, Sandor
Budapest University of Technology and Economics, Hungary
Keywords: beam-columns, modal decomposition, transverse stiffeners, end-plates, FE analysis

In the recent decades the numerical methods with modal decomposition ability gained certain popularity in the analysis of thin-walled structural members (beams or columns). Modal decomposition methods describe the displacements-deformations of the member by practically meaningful modes (such as global mode, local-plate mode, distortional mode, etc.) used as basis system. This approach helps in understanding the behavior, and has been found especially useful in understanding the buckling behavior. Moreover, properly selected modal deformation-displacement modes can strongly reduce the degrees of freedom of the problem. In the case of the two most known methods, i.e., the generalized beam theory and the constrained finite strip method, the modal decomposition is based on thin-walled beam theory, hence these methods can primarily be applied to beam-like problems. Practical (e.g., welded steel) beam or column members are frequently supplied with transverse plate elements, either as transverse stiffeners or as end-plates. From mechanical aspect the transverse elements are out of the realm of beam theories, therefore, structural members with added transverse plate elements are not yet handled by the existing modal decomposition methods. However, there is a newer method, the constrained finite element method, which can perform modal analysis, but which has a wide range of applicability, including members with transverse plate elements. In the paper some proof-of-concept examples are presented for the modal analysis of thin-walled members with transverse stiffeners and/or with end-plates.

11:15 am - 11:30 am

An analytical solution for the compressed simply-supported plate with initial geometric imperfections

Nedelcu, Mihai
Technical University of Cluj-Napoca, Romania
Keywords: simply supported plate, large deflections, analytical solution, initial geometric imperfections, effective width

The analytical solution of the uniformly compressed simply-supported plate was developed almost a century ago by various authors using the condition of minimum of the strain energy.

The resulted ultimate load was not in satisfactory agreement with the experiments.

Von Karman's semi-empirical approach considers that the ultimate load is reached when the critical stress of the effective width is equal with the yield stress.

Winter modified the formula in order to match the experimental results, and his expression is currently used in the majority of the CFS design codes.

The paper presents an accurate analytical solution using the initial approach but introducing different displacement functions.

The initial geometric imperfections are taken into account and their effect on the effective width is properly quantified.

11:30 am - 11:45 am

Plastic collapse loads of rectangular plate assemblies with constant and linear load distribution

Stehr, Sebastian; Stranghöner, Natalie
University of Duisburg-Essen, Germany
Keywords: plastic collapse load, rectangular plate assembly, EN 1993-1-7

Silos as agricultural structures are built as rectangular plate assemblies made of steel if there is the necessity for an easy mounting or if limited area is given. These silos serve for storage of e. g. liquids or solids. Depending on the contents, different load distributions on the vertical walls of a silo occur. Fluid loads are represented by a linear load distribution and solids can be described by Janssen patterns. These loads can lead to a plastic collapse of the structure. Current design standards for rectangular plate assemblies made of steel as EN 1993 1 7 and EN 1993 4 1 provide stress or deflection coefficients for only particular height over width ratios. Furthermore, they do not consider common boundary conditions or different load patterns. For this reason, numerical and theoretical investigations have been carried out at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen in the frame of the current revision of EN 1993-1-7 regarding the determination of plastic collapse loads of rectangular plate assemblies made of steel under different load cases (constant and linear load distribution as well as Janssen-distribution). For this reason,

numerical MNA parameter analyses have been carried out. For the evaluation of the plastic collapse load the methods of the modified southwell plot (MS) and convergence indicator plot (CIP) have been applied. The final objective is to derive analytical models for the description of the plastics collapse load depending on the load distribution. Within this contribution, first numerical and analytical results will be presented for constant and linear load distribution.

11:45 am - 12:00 pm

Enhanced buckling capacity of axially compressed, stiffened plates taking into account the shear-lag effect

Jäger-Cañás, Andreas
EHS beratende Ingenieure für Bauwesen GmbH
Keywords: plate, buckling, shear-lag

Compressed plates are typical elements of bridges and other built-up members. Optimized material distribution leads to wide and thin plates, which require sufficient stiffening. Due to the shear-lag effect, the compressive stress decreases from the side towards the center line of the plate. The stress in the center of the plate may be substantially smaller at the sides, which allows for optimized design of compressed plates. However, this is not widely applied.

For this paper a finite element parametric study has been conducted on stiffened plates of different aspect ratios. All studied geometries consisted of three equally spaced stiffeners of different dimensions, which were placed distant to each other but closely enough to not allow local buckling.

Loaded by an axial load as high as the yield stress as well as a fixed shear load, the cases studied are easily applicable to common stiffened bridge bottom flanges of hollow box cross-sections. The shear-lag effect has been studied in the domain from stress in the center to the side (ratio β) from 0.5 up 1.0 to cover most practically relevant cases.

The outcome of this study reveals that taking into account the shear lag effect, allows for considerably lighter designs than the typical engineer's approach with β equal to 1. Not only the reduced effective total load but as well the reduced stress of the stiffeners allow for a strength gain.

Numerical results are evaluated in compatibility with the frame work of current Eurocodes. Different approaches to achieve an optimized design are discussed. Finally, a procedure is developed, which allows to take into account the shear-lag effect in the analysis of axially compressed, stiffened plates using hand calculation procedures already given by EC 3-1-5.

12:00 pm - 12:15 pm

Statistical evaluation of the bearing capacity of polygonal short columns

Sabau, Gabriel[1]; Manoleas, Panagiotis[2]; Koltsakis, Efthymios[1]; Lagerqvist, Ove[1]

[1]Luleå University of Technology, Sweden; [2]Norwegian University of Science and Technology, Trondheim, Norway

Keywords: regular convex polygonal sections, statistical analysis, tubular towers, cold-formed

Regular convex polygon sections (RCPS) are commonly used as towers supporting transmission lines, stadium lightning and street lamps. Their use provides advantages in the bearing capacity and can simplify erection. Over the last 50 years experimental studies have been conducted to check the applicability of the plate theory to stocky polygonal columns. The paper presents the processed data gathered from compression tests found in the literature. Results from 67 specimens tested under pure compression were statistically analysed. Specimens with yield strength varying from 235 to 700 MPa and angles varying from 144 to 175.5 (5 to 40 sides) were investigated. The local non-dimensional slender-ness was calculated using buckling lengths according to EN 1993-1-3 and EN 1993-1-5 with values ranging from 0.6 to 6. The objective of the paper is to compare the plate buck-ling resistance predictions to the experimental results. The paper concludes with a buckling width recommendation for evaluating the critical stress as calculated according to EN 1993-1-3 or EN 1993-1-5.

TC8_1: Session of ECCS TC8 - 1

Time: Thursday, 12/Sep/2019: 10:30 am - 12:15 pm · Location: C202
Session Chair: Richard Stroetmann, Technische Universität Dresden
Session Chair: Andreas Taras, Bundeswehr University Munich

10:30 am - 10:45 am

About ECCS and its Committee TC8 on Stability of Steel Structures

Snijder, Bert
Eindhoven University of Technology, The Netherlands

Introduction to ECCS and its Committee TC8 on Stability of Steel Structures and the special sessions.

10:45 am - 11:00 am

Direct Strength Method (DSM) Design of Simply Supported Short-to-Intermediate Hot-Rolled Steel Equal-Leg Angle Columns

Dinis, Pedro Borges; Camotim, Dinar
Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
Keywords: Hot-rolled steel angle columns, Equal-leg angle columns, Simply supported columns, Ultimate strength, Direct Strength Method (DSM) design

This work reports the results of an ongoing investigation on the Direct Strength Method (DSM) design of hot-rolled steel equal-leg angle columns with simple supports (rigid end plates resting on spherical hinges) and short-to-intermediate lengths, i.e., exhibiting major-axis flexural-torsional critical buckling modes. It extends the scope of a similar study by the authors on cold-formed steel angle columns with the same characteristics, but exhibiting higher leg width-to-thickness ratios and containing non-negligible residual stresses. After collecting the experimental and numerical failure loads available in the literature, reported by various researchers and concerning columns with several geometries (lengths and cross-section dimensions), the paper briefly addresses the mechanical reasoning behind the development of an efficient (safe and reliable) DSM-based design approach proposed by the authors in the context of cold-formed steel short-to-intermediate angle column with fixed-ended and pin-ended (rigid end plates resting on cylindrical hinges allowing for minor-axis rotations) supports, which must be modified to handle the spherically-hinged simple supports - particular attention is paid to a modification/simplification of the expressions providing the design curves previously developed by the authors. Then, the collected failure load data are used to assess the quality of their estimates provided by the proposed DSM-based design approach, including the determination of the corresponding Load and Resistance Factor Design (LRFD) resistance factor. It is shown that the proposed design approach successfully predicts the hot-rolled steel simply supported (spherically-hinged) angle column failure loads assembled in this work - moreover, these predictions lead to LRFD resistance factors above or equal to 0.90 (value recommended by AISC for compression members), a very encouraging outcome

of this research effort. However, further validation, against a larger set of experimental (mostly concerning columns with intermediate and high slenderness) and numerical failure load is indispensable before the above DSM-based design approach can be considered for codification.

11:00 am - 11:15 am

Appropriate spring stiffness models for the end support of bolted single steel angle members in compression

Kettler, Markus; Unterweger, Harald; Harringer, Thomas
Graz University of Technology, Austria
Keywords: angles, buckling

Single steel angles with bolted end-connections are often used as bracing members in trusses and frames for buildings or in lattice transmission towers, because they can be fabricated and erected very easily and very quickly. The eccentric connection on only one leg induces additional bending moments leading to a complex load carrying behaviour, especially for compression members.

Preliminary numerical and experimental investigations by the authors have highlighted the fact that the stiffness of the rotational restraints at the gusset plate near the member's ends are crucial for the prediction of the compression member capacity. Consequently, analytical models for the estimation of appropriate spring stiffness values have been developed for several practical applications in buildings and two-bolt connections at both member's ends. Within this paper the developed formulae are presented alongside with a detailed background of their derivation. The formulated stiffness values can in future be used to improve the accuracy of the prediction of the compression member capacity of single steel angles with bolted end-connections.

Finally, the paper exemplarily shows the potential increase in capacity compared to the simply supported reference case. It will be shown that with the help of the newly developed stiffness models both safe and economical results are achieved.

11:15 am - 11:30 am

Stability Design of Cable-Stayed Columns

Tankova, Trayana; Simões da Silva, Luís; Martins, João Pedro
ISISE – Department of Civil Engineering, University of Coimbra, Portugal
Keywords: Pre-stressed stayed columns, steel, member design

Pre-stressed stayed columns have several advantages among traditional ones: they have enhanced buckling resistance in comparison to conventional columns provided by the pre-stressed cables and cross-arms; therefore, they can be applied with higher lengths. This benefit can be strategically applied using high strength streel, providing an economic solution. The pre-stressed stayed columns are also aesthetically appealing, combining a strong architectural effect with top notch of engineering solution.

The stability behaviour of this structural solution been studied since the second part of 20th century. The research covers analytical derivations and experimental tests, and lately results by advanced numerical simulations. However, regarding the design of these columns, the guidance is limited or incomplete.

In this paper, design rule for stability design of pre-stressed cable-stayed columns is presented. It is based on the well-known Ayrton-Perry format, i.e. on a combination of first and second order effects. It is consistent with the design rules for uniform columns in Eurocode 3. It accounts for the geometry of the column, the applied pre-stress and it also covers symmetrical and anti-symmetrical buckling modes of these columns.

11:30 am - 11:45 am

Buckling and Strength of Prestressed Steel Stayed Columns

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Corresponding author: machacek@fsv.cvut.cz
Keywords: buckling, stayed column, imperfection, inelastic, prestressing

Prestressed steel stayed columns have been used since fiftieth of the last century to enhance their critical and maximal capacities in compression. This research deals with central steel tube columns, one and two tube crossarms and spatial prestressed rod or cable stays. Firstly four columns made of stainless steel 1.4301 with one central crossarm and cable stays were tested up to extreme buckling deflections. The following numerical analysis employed geometrically and materially nonlinear analysis with imperfections (3D GMNIA) using ANSYS software. Careful analysis was successfully validated and used to obtain optimal prestressing of stays giving maximal critical loads and maximal collapse loads of the tested columns. All the following parametrical studies cover columns of the same geometrical and nonlinear material characteristics as given or resulted from testing. This enables comparison and evaluation of the significance concerning mode and value of initial deflections, value of prestressing, number of crossarms, material characteristics, sliding of stays at crossarms and ratios of maximal collapse to critical loads. The main results

concerning critical loads of an "ideal column" (with amplitudes of initial deflections L/500000) and maximal loads of an "imperfect column" (with amplitudes of initial deflections L/200) under various prestressings of stays are discussed in a detail. In the conclusions a necessity of GNIA/GMNIA considering respective mode and value of initial de-flections is emphasized (linear buckling analysis is not sufficient in such prestressed elements). Also the substantial significance of activating of stays during buckling and radical increase of both critical/maximal loads by adding the second crossarm is presented.

11:45 am - 12:00 pm

Effect of the steel grade on equivalent initial imperfections for lateral-torsional buckling

Winkler, Rebekka; Knobloch, Markus
Ruhr-Universität Bochum, Institute of Steel, Lightweight and Composite Construction, Germany
Keywords: lateral-torsional buckling, member imperfections, high strength steel

The equivalent initial imperfections of EN 1993-1-1:2005 were developed based on studies considering steel grades up to S460. For flexural buckling an extension of the scope of the verification method to higher steel grades up to S700 is currently being evaluated in the context of the revision and further development of Eurocode 3. For LTB, however, similar studies, are still lacking.

This paper presents a comprehensive study on the development of equivalent initial imperfections for high-strength steel members subjected to lateral torsional buckling. The study focuses on members with hot-rolled double symmetric I-/H-cross sections of steel grade S700. The proposed imperfections and their application to verification methods are compared to existing design approaches. In addition to normative rules applied in Europe, a novel design approach is also taken into account, which is currently discussed as part of the further development of Eurocode 3. Furthermore the paper provides a new proposal for LTB-imperfections and the additional consideration of steel grades up to S700 using the partial internal forces method. This proposal leads to design results that fit well with the results of numerical simulations.

12:00 pm - 12:15 pm

Experimental study of cold-formed high strength steel circular hollow sections

Meng, Xin; Gardner, Leroy
Imperial College London, United Kingdom
Keywords: high strength steel, CHS

An experimental study into the cross-sectional behaviour of cold-formed high strength steel circular hollow sections (CHS) is described in this paper. A total of six CHS profiles with steel grades of S700 was examined, spanning from Class 1 to 4 (in compression) according to Euro-code 3. The investigation consisted of twelve tensile coupon tests, six stub column tests, fifteen short beam-column tests, six four-point bending tests and six three-point bending tests. The obtained experimental results revealed that the studied CHS were all capable of reaching the plastic cross-section capacities under the considered loading scenarios, and their resistances under moment gradients were shown to be on average 8% higher than those under constant moments.

Poster session

Time: Thursday, 12/Sep/2019: 1:30 pm - 2:00 pm · Location: Atrium

Buckling length assessment with finite element approach

Tiainen, Teemu; Mela, Kristo; Heinisuo, Markku
tampere university of technology, Finland
Keywords: buckling length, effective length

In the design of steel frames, the consideration of stability and buckling is an important issue. It can be done in multiple ways. If the concept of buckling length is used, widely used procedure is to calculate the eigenmodes and corresponding eigenvalues for the frame and by using them define buckling length of the members with the well-known Euler's equation. However, it maybe difficult to tell, which eigenmode should be used for the definition of the buckling length of a specific member. Conservatively, the lowest positive eigenvalue can be used for all members.

In this contribution, two methods to define the buckling length of a specific member are considered. The first one uses geometric stiffness matrix locally and the other one uses strain energy measures to identify members taking part in a buckling mode. Compared to simplified approaches presented in literature the approaches based on the finite element discretization have certain advantages. First, the method is applicable to any kind of distributed loading. Secondly, also tapered members can be handled with the technique. Moreover, the out-of-plane buckling behavior and with suitable element the lateral buckling loads can be also be assessed.

The applicability and features of the methods are shown in several numerical examples. Both methods can be relatively easily implemented into automated frame design procedure. This is essential when optimization of frames is considered.

Development of an innovative multi-performance system for LWS structures

Campiche, Alessia
University of Naples "Federico II", Italy
Keywords: CFS, Innovative lateral force resisting system, High strength steel

Nowadays the key topics of the construction sector are safety and eco-efficiency. In the last decades, the Lightweight Steel (LWS) systems made of Cold Formed Steel (CFS) pro-files have shown high structural and environmental performances, joining perfectly the new trend. In this perspective, the University of Naples “Federico II”, in cooperation with Lamieredil S.p.A. Company, has recently started a new research project. The main goal of the project is the development of a new solution with high seismic and environmental performances. From the structural point of view, the innovation consists in a CFS profile wall, equipped with pre-tensioned Ultra High Strength (UHS) steel braces, which are able to limit global displacement of structure and to dissipate seismic

energy by its yielding. The effectiveness of the wall system will be proved through several tests carried out at Lab of the Department of Structures for Engineering and Architecture. The experimental activity will include tests on materials and assemblies, monotonic and cyclic tests on full-scale components and shake-table tests on a building mock-up. From the environmental point of view, more appropriate materials for the envelope will be selected and production and erection processes of the system will be analysed, in order to obtain higher acoustic and thermal performances and reduction of waste. As a conclusion, a prototype building will be erected, tested and monitored on the company property. The paper summarizes the research project in detail, the experimental program and the design of the innovative sys-tem and prototype.

Experimental verification of lateral-torsional buckling of steel I beam with tapered flanges

Kuś, Juliusz
Opole University of Technology, Poland
Keywords: tapered I-beam, stability, lateral-torsional buckling

Tapered steel beams and columns are commonly applied in modern steel structures due to their less weight and more optimal solutions of the structural designs. That is why effective engineering solutions of the problem of their capacity is expected. The General rules and rules for buildings of part 1-1 of Eurocode 3 constitute the core of the code procedures for the design of steel structures. They contain the basic guidance for structural modelling and analysis of steel elements and the rules for the evaluation of the resistance of structural members subject to different loading conditions. Design of tapered beams with tapered web or flanges is more complex than for prismatic members for the two reasons: analytical expressions for the elastic critical loads are not readily available and the choice of the critical section for the application of the buckling resistance formulae is not straightforward.

In the paper proposed for the Conference a procedure for calculation critical buckling moments for flange-tapered I-beams is demonstrated. Detailed examples are carried out. Typical engineering, uniformly distributed design loads are considered for load applied to the top flange, shear centre, as well as to the bottom flange. In addition, results of experiment are presented and compared with analytical solution for simply supported flange-tapered I-beam.

Seimic design of two-storey X-bracings

Costanzo, Silvia; D'Aniello, Mario; Gianmaria, Di Lorenzo; Attilio, De Martino; Raffaele, Landolfo

Univeristy of Naples Federico II, Italy, Department of Structures for Engineering and Architecture

Keywords: concentrically braced frames; 2-storey CBF, Split X-CBF, Eurocode 8; capacity design; bracings; ductility; seismic design

2-storey X-bracings are becoming very popular in European practice, owing the possibility to reduce the large bending demand typically observed on the brace-intercepted beam in V and inverted-V configurations. However, they are not properly addressed within the current Eurocode 8, and specific design provisions are missing. The research presented in this paper is addressed to deepen the most critical issues affecting the seismic behaviour of 2-story X concentrically braced frames and to identify the most effective design rules to assure satisfactorily seismic performance. Seismic design criteria are proposed and numerically investigated. In detail, a comprehensive numerical parametric study is carried out considering a set of planar frames extracted by low, medium and high-rise buildings alternatively designed according to five different design procedures. Results from nonlinear dynamic analyses confirm the proposed design criteria assure adequate seismic performance.

Laser technology for innovative connections in steel construction – an overview of the project LASTEICON

Degée, Hervé[1]; Kanyilmaz, Alper[2]; Calado, Luis[3]; Castiglioni, Carlo[4]; Couchaux, Maël[5]; Hjiaj, Mohammed[5]; Hoffmeister, Benno[6]; Morelli, Francesco[7]

[1]Hasselt University, Belgium; [2]Politecnico di Milano, Italy; [3]IST Lisboa, Portugal; [4]Fincon Consulting Italia, Italy; [5]INSA Rennes, France; [6]RTWH Aachen, Germany; [7]University of Pisa, Italy

Keywords: Tubular structures, Beam-to-CHS connection, Hollow section joints, Laser cutting

Circular hollow sections present several advantages, such as uniform behavior in all directions or possibility to obtain composite behavior by concrete infill, and hence high strength, stability and good fire resistance. Moreover, their aesthetic appeal has a great potential for decision makers (architects, building owners...). However, their adoption in the practice often suffers from the complexity and high cost of their joint detailing. The ongoing RFCS-funded project Lasteicon aims at proposing a novel and rather simple jointing solution with reduced complexity and fabrication costs, to be adopted for connections between CHS-columns and I-beams or for truss structures with CHS chords. The proposed solution relies on a versatile laser cutting and welding technology.

The present contribution plans to give a broad overview of the main outcomes of the project reached so far and covers the following aspects: assessment of fabrication procedures and tolerances, experimental testing on 2-ways and 4-

ways steel joint as well as on 2-ways composite and trusses configurations, results of a broad numerical investigation and comparison with traditional design and fabrication methods in terms of structural performances in normal and cyclic loading, life cycle assessment and economical aspects.

Proposal for improving the consistency between Eurocode 3-1-8 and Eurocode 8-1

Stratan, Aurel; Dubina, Dan
Politehnica University of Timisoara, Romania
Keywords: seismic design, connection, Eurocodes, structural analysis

This paper makes on overview of provisions for design of joints in steel structures according to EN 1993-1-8 and EN 1998-1 and discusses the relationship between the two codes. EN 1993-1-8 provides detailed design criteria and guidance on modelling of joints for global structural analysis, being limited to joints subjected to predominantly static loading. On the other hand, EN 1998-1 provides additional requirements for seismic design of joints in steel structures, to-tally relying on design tools from EN 1993-1-8. Several inconsistencies between the two codes concerning calculation of design resistance, modelling and strength classification are discussed in this paper, and possible improvements are proposed.

Studying bolt force distribution in ultra-large capacity end-plate connections

RAMZI, Ahmed; El Aghoury, Ihab; Ibrahim, Sherif; El-SERWI, Ahmed
ASU, Egypt
Keywords: Moment Connections, Ultra High Capacity Connections, Bolt Force Distribution

Bolted connections are classified according to their flexural resistance and rotational stiffness. The moment capacity of any connection is controlled by its different components (end-plate thickness, bolt diameter, bolt grade and stiffeners (if any)). Increasing the number of bolts in the tension zone achieves a higher moment capacity for the connection. In this paper, the ultra-large capacity connection with 12 bolts in tension (4 bolts per row) is studied. A proposed finite element model was built and verified using experimental results. A parametric study is carried out using different parameters: end-plate thickness, bolt diameter, effect of horizontal stiffeners and their thickness. Results are presented in the form of curves using the relation between end-plate thickness and the moment capacity for different parameters. Moreover, bolt force distribution is studied at yielding and ultimate limit of connection. Results showed that the chosen parameters are effective on moment capacity and bolt force distribution among bolts.

Experimental verification of shear connection of thin-walled steel built up members

Horáček, Martin; Melcher, Jindřich
Brno University of Technology - Faculty of Civil Engineering, Czech Republic
Keywords: beam, bending, shear connection, thin-walled profiles

The current trend in the design of steel structures leads, due to the saving of the material, to the frequent use of thin-walled cold formed steel sections. The majority of thin-walled steel profiles has a mono symmetrical cross-section, with the bending stiffness of the cross-section to the symmetry axis often higher than the bending stiffness to an axis perpendicular to the axis of symmetry. By a suitable choice of the cross-sectional shapes and their shear connection (very often by means of bolted joints), the built up thin-walled cross-sections can be created. These built up sections are usually double symmetrical and their bending stiffnesses to the axes of symmetry are of same order. The subject of this article is an experimental investigation and evaluation of the shear connection of a pair of profiles with different number of fasteners and their arrangement.

Fatigue failure of skew beam grid steel bridges – causes and assessment

El Aghoury, Mohamed[1]; El Aghoury, Ihab[2]; El Hady, Amr[3]
[1]Structural Engineering & Construction Management Dept., Future University in Egypt, Cairo, Egypt; [2]Department of Structural Engineering, Ain Shams University, Cairo, Egypt; [3]Higher technological institute, Tenth of Ramadan city, Egypt
Keywords: Skew Steel Bridges, Fatigue detail category, Skew Stiffeners, Splice plates

The aim of this research is to investigate the causes of failure of Mansoura-Belkas roadway bridge junction. This junction is one of 4 similar junctions between the bridge and the crossing two highway roads. The junction consists of skew beam grid steel bays. The structural system of the grid consists of 3 main girders connected to each other by highly skewed cross girders connected by skew web stiffeners. Due to the subsequent overloaded trucks passing over the junction for a considerable period; the failure of two out of three main girders occurred near the main girder splices (which are not at the mid-span).

By investigating the design capacity of the girders, it was evident that the failure wasn't just due to overloading. Since the failure of the bridge took place only 8 years after its construction, a fatigue life assessment was conducted. The assessment showed that the fatigue detail category of the highly skew web stiffener connection was highly reduced which needed a thorough investigation. Thus, a finite element model is developed to accurately model the stress transition zone near the splices close to the skew web stiffeners at the connections between main girders and the cross girders. A small parametric study was also conducted to investigate the effect of different parameters on

the stress concentration factors. Several observations, conclusions and some practical recommendations for designers are given.

Numerical investigation of steel Built-up Columns Composed of Track and Channel Cold-Formed Sections

El Aghoury, Mohamed[1]; Amoush, Essam[2]; El Hady, Amr[2]; Ibrahim, Sherif[3]

[1]Structural Engineering & Construction Management Dept., Future University in Egypt, Cairo, Egypt; [2]Department of Structural Engineering, Higher Technological Institute, Tenth of Ramadan City, Egypt; [3]Structural Engineering Dept., Faculty of engineering, Ain Shams University, Cairo, Egypt

Keywords: Cold-Formed Sections, Track Sections, built-up columns and finite element modelling

As one of the typical building structures, cold-formed steel structures become increasingly popular in recently years due to their superior strength to weight ratio and ease of construction together. Also it is a convenient choice for compression member in cold-formed steel construction. In this paper, a relatively new built-up columns cross-section composed of double lipped channel assembled with flanges of double back to back track sections which subjected to axial compressive load is suggested. Section nominal thicknesses ranging from 0.48 mm to 1.5 mm, is suggested. The cross-sectional geometries were assembled by using sufficient number of bolt interconnectors either at the flanges or webs, depending on the sectional configurations is considered. The interconnectors spacing was varied among specimens of the same cross-sectional geometry. A numerical analysis and verification models of previously tested built-up cold-formed columns are carried out by using 'ANSYS' software. Numerical studies were carried out to investigate the strength of the built-up columns which depended on different parameters such as cross-section component aspect ratios and overall slenderness ratios with various column lengths of the suggested built-up columns. The initial geometric imperfections of each specimen was considered. The FE models were further used to quantify the effect of the fastener interconnector layouts on composite action and behavior buckling response of cold-formed steel built-up columns. In general, the models were failed by local buckling and interaction between local and flexural buckling. The ultimate strengths of the models were compared with the column strengths predicted using direct strength method.

Fire 2: Fire

Time: Thursday, 12/Sep/2019: 2:00 pm - 3:30 pm · Location: C204
Session Chair: Hervé Degée, Hasselt University
Session Chair: Carlos Couto, University of Aveiro

2:00 pm - 2:15 pm

Numerical simulation and analysis of axially restrained stainless steel beams in fire

Pournaghshband, Asal[1]; Afshan, Sheida[1]; Theofanous, Marios[2]
[1]Brunel University London, London, United Kingdom; [2]University of Birmingham, Birmingham, United Kingdom
Keywords: Stainless steel beam, Catenary action, Fire, Restraint forces, Numerical modelling

This paper reports the results of a numerical investigation into the response of restrained stainless steel beams in fire, where in addition to the degradation of strength and stiffness at elevated temperatures, the influence of thermally induced stresses, are also included. The finite element (FE) programme ABAQUS has been used to model stainless steel welded I-section beams of different axial end restraint stiffness subjected to fire. The FE models are firstly validated against a selection of literature test data, and then used to perform parametric studies. The generated models capture the effects of restrained thermal deformations with a high degree of accuracy, and thereby allow the influence of frame continuity to be explicitly considered in design of stainless steel members in fire to quantify the required strength and ductility demands on connections for catenary action to develop. Comparisons with carbon steel beams demonstrate that while stainless steel beams show similar stages of behaviour in fire, they are capable of withstanding higher temperatures prior to the onset of catenary action, while developing similar levels of maximum tensile catenary force to carbon steel beams, despite the higher thermal expansion of the material.

2:15 pm - 2:30 pm

Buckling of Circular Hollow Section Stainless Steel Columns in Fire

Mohammed, Asif; Afshan, Sheida
Brunel University London, United Kingdom
Keywords: Stainless steel, Fire, Finite element analysis, Structural fire design, Reliability analysis.

Stainless steel tubular sections are being increasingly used in engineering applications, due to their unique strength, durability, ductility and aesthetic appeal. In addition, stainless steel offers high retention of strength and stiffness at elevated temperatures compared to its counterpart carbon steel. From the limited existing test data on stainless steel circular hollow sections (CHS) columns in fire, it has been observed that the current Eurocode 3 provisions can be unconservative in their capacity predictions, which use the design formulations for carbon steel members, despite stainless steel having different material behaviour. A numerical modelling study has been undertaken using the finite element (FE) package ABAQUS to study the stability of stainless steel CHS members at elevated temperatures. The FE models were first validated against the experimental data from the literature and subsequently used to perform parametric studies at member level. The results have been compared with the design provision in Eurocode 3 Part 1-2, and improved design recommendations have been proposed. Reliability analysis has been carried out to confirm the suitability of the design proposals.

2:30 pm - 2:45 pm

Ultimate Strength Analysis of Steel-Concrete Cross-Sections at Elevated Temperatures

Chiorean, Cosmin-Gruia; Selariu, Mihai Dorin; Buru, Marius
Technical University of Cluj-Napoca, Romania
Keywords: Ultimate strength, Heated Cross-section, Strain-softening, Steel-Concrete

This paper presents a new computational method for ultimate strength analysis of compo-site steel-concrete cross-sections with arbitrary shape subjected to elevated temperatures. The analysis method is carried out in two main steps: (i) thermal analysis, used to evaluate the temperature distribution throughout the cross-section at a specific time and (ii) mechanical analysis, in which the interaction diagrams are determined. The main feature of the proposed approach consists in controlling the inelastic response at the strains level enforcing in the same time the elasto-plastic equilibrium for a prescribed axial force and bending moments ratio. The ultimate (maximum) strength capacity is formulated as a problem of unconstrained mathematical optimization by applying the method of Lagrange multipliers. The optimized function is defined as a total internal bending moment and two constrains are defined by enforcing the constant axial force and bending moment ratio. Hence, the ultimate bending moment capacities are directly obtained by solving just three coupled nonlinear equations. The developed procedure has been used to predict the bending

moment capacity diagrams of several cross-sections under fire actions and the comparisons made prove the effectiveness and the reliability of the proposed method of analysis.

2:45 pm - 3:00 pm

Numerical advanced analysis of steel-concrete composite beams and columns under fire

Barros, Rafael[1]; Silveira, Ricardo[1]; Pires, Dalilah[2]; Lemes, Ígor[3]; Berke, Péter[4]; Rocha, Paulo[1]

[1]Federal University of Ouro Preto; [2]Federal University of São João del Rey; [3]Federal University of Lavras; [4]Université libre de Bruxelles

Keywords: Advanced fire analysis, composite structures, CS-ASA/FA, CS-ASA/FSA, strength limit and stability

It is well known that high temperature causes changes in physical properties and mechanical strength of the materials used in the structures. In both steel and concrete, such characteristics deteriorate during the exposure to fire, and the structure load capacity and stiffness are reduced significantly with the increasing temperature. This work is on advanced thermal-structural analysis of composite (steel and concrete) beams and columns, and it aims to show the new capabilities of the program CS-ASA (Computational System for Advanced Structural Analysis) to dealt with composite structures under high temperature. The use of advanced analysis as a numerical methodology of analysis/design has as advantages the capture of strength limit and stability of a structural system and its members directly. To achieve the objective, the two new CS-ASA modules for composite structures are presented: CS-ASA/FA (Fire Analysis) and CS-ASA/FSA (Fire Structural Analysis). The first aims to determine the temperature field in the cross section of the composite structural elements by FE thermal analysis; the second aims to perform the inelastic second-order analysis of composite structures under fire considering the refined plastic hinge method (RPHM) coupled to strain compatibility method (SCM). For a more comprehensive validation of the implemented modules, various composite beam and columns in fire situation are analyzed.

3:00 pm - 3:15 pm

The Fire Behavior of Extended Stiffened Joint Designed for Seismic Actions

Linguiti, Alessia[1]; Tartaglia, Roberto[1]; D'Aniello, Mario[1]; Wald, František[2]; Landolfo, Raffaele[1]

[1]University of Naples Federico II, Italy; [2]Czech Technical University in Prague

Keywords: extended stiffened joint; seismic behavior; fire design; finite element analysis

The structural behavior of steel moment resisting frames (MRFs) is strongly dependent on the beam-to-column joint behavior. The role of the joints is crucial especially under accidental natural and human induced actions, as in the cases of earthquake and fire scenarios, which can occur subsequently after severe seismic events in urban areas.

The study summarized in this paper aims at investigating the fire behaviour of seismically designed extended stiffened end-plate joint by means of finite element analyses (FEAs). The joint performance was investigated considering two possible scenarios: (i) in the first case the assemblies were subjected only to the fire action; (ii) in the second scenario the fire actions were applied to seismically damaged joints. The numerical results show that the fire action change the restrain capacity of the joint, and local failure can also occur, especially when fire occurs after severe seismic damage.

3:15 pm - 3:30 pm

A quasi-static nonlinear analysis for assessing the fire resistance of steel 3D frames exploiting time-dependent yield surfaces

Magisano, Domenico; Leonetti, Leonardo; Liguori, Francesco; Garcea, Giovanni
UNICAL, Italy
Keywords: 3D frames, yield surface, incremental analysis, fire, fire resistance

In this work an automatic procedure for evaluating the axial force-biaxial bending yield surface of steel sections in fire is proposed. It provides an accurate time-dependent expression of the yield condition by a section analysis carried out once and for all, accounting for the strength reduction of the materials, which is a function of the fire duration.

The equilibrium state of 3D frames with such yield conditions, once discretized using beam finite elements, is formulated as a nonlinear vectorial equation defining a curve in the hyperspace of the discrete variables and the fire duration. A generalized path-following strategy is proposed for tracing this curve and evaluating, if it exists, the limit fire duration, that is the time of exposure which leads to structural collapse. Compared to the previous proposals on the topic, which are limited to local sectional checks, this work is the first to present a global analysis for assessing the fire resistance of 3D frames, providing a time history of the fire event and taking account of the stress redistribution. Numerical examples are given to illustrate and validate the proposal.

PI2: Plates: shear, patch loading; Shells

Time: Thursday, 12/Sep/2019: 2:00 pm - 3:30 pm · Location: C206
Session Chair: Rolando Chacón, Universitat Politècnica de Catalunya
Session Chair: M. Kotelko, Lodz University of Technology

2:00 pm - 2:15 pm

Nonlinear finite element analysis of delta girders subjected to patch loading

Loaiza, Nelson[1]; Graciano, Carlos[1]; Casanova, Euro[2]
[1]Universidad Nacional de Colombia, Facultad de Minas, Sede Medellín, Departamento de Ingeniería Civil, A.A. 75267, Medellín, Colombia; [2]Universidad del Bío-Bío, Departamento Ingeniería Civil y Ambiental, Avenida Collao 1202, Código Postal 4051381, Concepción, Chile
Keywords: Patch loading, Finite element analysis, Plate girders, Delta girders, Longitudinal stiffeners

Recent investigations related to plate girders design have demonstrated that is possible to increase the flexural and shear resistance by using delta stiffeners. This type of reinforcement also increases the torsional rigidity of the plate girder reducing lateral deformation. However, the impact of delta girders subjected to pure patch loading has received little attention. Therefore, this paper aims at studying the postbuckling behaviour and comparing the patch loading resistance of longitudinally stiffened girders and delta girders, evaluating the influence of different geometrical parameters such as the panel aspect ratio, the patch loading length and the position of the longitudinal stiffener. To this purpose, a nonlinear finite element model is developed considering geometrical and material imperfections. The computed ultimate resistances are validated against experimental results found in the literature. Based on the results, design recommendations are presented for delta girders under patch loading.

2:15 pm - 2:30 pm

CRITICAL BUCKLING LOAD ON TRANSVERSALLY AND LONGITUDINALLY STIFFENED STEEL PLATE GIRDERS SUBJECTED TO PATCH LOADING

Herrera, Juan; Chacón, Rolando
Universitat Politècnica de Catalunya, Spain
Keywords: Patch loading; EN1993-1-5; transverse stiffening, longitudinal stiffening, plate buckling

The patch loading resistance model that is available in European design rules EN1993-1-5 may lead to a significant underestimation of the resistance in the case of plate girders with closely spaced transverse stiffeners. This has been considerably investigated for transversally stiffened girders but less information is available for the case of girders with both transverse and longitudinal elements. When studied separately (transversally and longitudinally stiffened), predicting models that estimate both critical and ultimate load capacities have been proposed. However, for the case of girders in which the problem is dealt

with coupled, the critical buckling load estimation method is particularly affected by the existing geometrical limitations b1/hw≤0,3 and 0,05≤b1/a≤0,3. Outside these boundaries, the literature does not provide any information on how to proceed. While it is recognized that the vast majority of realistic girders have panels with proportions among these limits, in some cases, these conditions are not fulfilled. The focus of this investigation is on a practical estimation of the critical buckling load on girders with proportions outside of these boundaries. The study is based on numerical parametric analysis covering a vast amount of proportions encompassing both transverse and longitudinal stiffening.

2:30 pm - 2:45 pm

Experimental and numerical studies on shear behaviour of stainless steel plate girders with inclined stiffeners

Chen, Xiaowan[1]; Yuan, Huanxin[1]; Real, Esther[2]; Du, Xinxi[1]

[1]Wuhan University, People's Republic of China; [2]Universitat Politècnica de Catalunya, Spain

Keywords: Inclined stiffeners; plate girders; stainless steel; shear buckling behaviour

Experimental and numerical studies on shear buckling behaviour of stainless steel plate girders with inclined stiffeners have been carried out in this study. Material properties of the two adopted stainless steel alloys, including austenitic grade EN 1.4301 and duplex grade EN 1.4462 were obtained, and initial geometric imperfections of the cross-sections were deter-mined. Two stainless steel plate girders with inclined stiffeners were tested under simply sup-ported conditions. The critical buckling strengths and ultimate shear resistances were all obtained and further compared to those of previously tested plate girders with transverse stiffeners only and both transverse and diagonal stiffeners. Elaborated finite element (FE) models developed by means of the FE software package ABAQUS were validated against the obtained experimental results. The validated FE models was subsequently used to evaluate the influence of the stiffener inclination on the load-carrying capacity of plate girders.

2:45 pm - 3:00 pm

Experimental and numerical investigations of unstiffened steel girders with non-rectangular panels subjected to bending and shear

Pourostad, Vahid; Kuhlmann, Ulrike
Institut of Structural and Design, University of Stuttgart
Keywords: plate buckling, numerical simulations, experimental investigations, multiaxial stress state, M-V interaction, tapered girders, nonrectangular panels

Slender structures of thin plates are usually designed according to EN 1993-1-5. In order to adapt to an optimized overall curved shape in the longitudinal direction of bridges with plated girder the development of buckling rules for non-rectangular steel panels is addressed. This paper aims to show experimental as well as numerical analyses on the buckling behaviour of nonrectangular panels, which are conducted in the frame of a European Research Project OUTBURST (OpTimization of Steel Plated BRidges in Shape and Strength). To investigate the behavior of the non-rectangular panels, six large tests composed of unstiffened and stiffened girders have been conducted at the laboratory at the University of Stuttgart. The numerical simulations are validated by recalculation of the tests. In addition, to investigate the effect of angle, aspect ratio and slenderness of panels on the buckling behavior of tapered panels subjected to the interaction of bending and shear, a parametric study is conducted for unstiffened panels. Different resistance models are developed and statistically evaluated. A resistance model and design procedure on basis of the EN 1993-1-5 in case of non-rectangular panels is proposed to achieve a safe and economic design.

3:00 pm - 3:15 pm

Plastic buckling of moderately thick circular rings under uniform lateral loading

Guarracino, Federico
University of Naples "Federico II", Italy
Keywords: ring buckling, plastic instability, experimental testing

Evaluation of the critical external uniform loading for a circular ring occurs frequently in a wide range of structural problems and as a consequence it has been extensively treated in a large number of works. Since the available results in literature result often scattered and not always consistent, a number of hoc ad experimental tests have been carried out by means of a newly patented apparatus in order to highlight the main features of the plastic collapse mechanism for rings of moderate thickness. The experiments are reported and interpeted with the aid of analytical and numerical analyses. The role of initial imperfections and variations in material strength are analysed in detail and formulae are provided to account for their influence.

3:15 pm - 3:30 pm

Considering Realistic Weld Imperfections in Bearing Capacity Calculations of Ring-Stiffened Shells using the Analytical Numerical Hybrid Model

Pasternak, Hartmut[1]; Li, Zheng[1]; Stapelfeld, Christoph[1]; Jäger-Cañás, Andreas[2]; Launert, Benjamin[1]

[1]Brandenburg University of Technology, Germany; [2]EHS beratende Ingenieure für Bauwesen GmbH, Lohfelden, Germany

Keywords: Ring-Stiffened Silos; Analytical Numerical Hybrid Model; Weld Imperfection; Bearing Capacity; Steel Structures

The ring-stiffener is widely used to prevent the local and global buckling in silos and tanks. For their assembly, welding is one of the most common techniques in steel structures. However, the welding process inevitably also produces residual stresses and distortions. These structural and geometrical imperfections influence the buckling capacity of stiffened silos. Since they are in most cases thin walled structures, they are known to be very sensitive to imperfect initial geometries. Nowadays, for the calculation of residual stresses and weld distortions, welding simulation can provide satisfactory results. At the same time, due to the huge requirement of calculation time and storage capacity, the 3-D welding simulation is difficult to apply directly to the analysis of real large structures. The analytical numerical hybrid model provides an alternative fast and simply applicable approach for the calculation of weld imperfections. The approach is subdivided into an analytical calculation of mechanical loads representing the thermomechanical effects caused by welds and then a subsequent numerical calculation of the stresses and deformations with these loads. In this paper, the application of this model is demonstrated on an exemplary buckling capacity calculation of a silo structure with ring stiffeners. First, by means of a parametric study applying different heat inputs per unit length and different welding sequences, recommendations for a subsequently planned experimental study are proposed targeting the lowest imperfections. Finally, numerical calculations of the axial load bearing capacity of the welded silo specimen are carried out to show the results under consideration of these results with the analytical numerical hybrid model.

TC8__2: Session of ECCS TC8 - 2

Time: Thursday, 12/Sep/2019: 2:00 pm - 3:30 pm · Location: C202
Session Chair: Markus Knobloch, Ruhr-Universität Bochum
Session Chair: Leroy Gardner, Imperial College London

2:00 pm - 2:15 pm

Stability of double symmetric sections subjected to axial force, bending moments and torsion

Jörg, Fabian; Kuhlmann, Ulrike
University of Stuttgart, Germany
Keywords: double symmetric sections, stability, numerical simulations, experimental investigations, torsion, N-M-T-Interaction

Double symmetric steel sections as rolled sections, are most important components used in steel buildings such as industrial halls. Due to their high load bearing capacity and their flexibility resulting from a large product line-up, they are used nowadays for columns and trusses as well as for purlins and crane girders. Due to their slenderness, the sections are often vulnerable for buckling and are also confronted with various external influences resulting in combinations of different internal forces. This can be illustrated quite well by the example of a crane girder. The crane girder is subjected to dual-axis bending stresses with an additional torsional moment, due to horizontal load application at the top flange. Moreover axial forces in longitudinal direction of the girder occur through acceleration and brake-application of the crane.

Currently, several design requirements exist to prove buckling resistance, however, these are often too complicated for practical application, e.g. finite element calculations or in case of the equivalent member method in Eurocode 3 do not include all internal forces.

Within the framework of a research project (Interactions for axial force, bending moments and torsion: harmonization and proof of stability for double symmetric sections), different work packages are planned to develop extended dimensioning rules based on the Eurocode 3 Part 1-1 which allow practical calculations of interactions of axial force, bending moments and torsion and may still be dealt without a finite element analysis. To investigate the stability behavior, 12 tests have been realized at the laboratory at the University of Stuttgart, composed of three different double symmetric sections with varying load eccentricities. These tests have been recalculated numerically. With this validated numerical model further investigations in form of a large parameter study were carried out in order to analyze an appropriate design approach according to EN 1993-1-1 on double symmetric sections subjected to axial force, bending moments and torsion. The solution for N-M-T presented in Annex C of the new draft is also considered.

2:15 pm - 2:30 pm

Experimental study on LTB behaviour and residual stresses of welded I-section members

Schaper, Lukas[1]; Jörg, Fabian[2]; Winkler, Rebekka[1]; Kuhlmann, Ulrike[2]; Knobloch, Markus[1]

[1]Ruhr-Universität Bochum, Germany; [2]Universität Stuttgart, Germany

Keywords: lateral torsional buckling, residual stress

This paper addresses results of an experimental study related to the lateral torsional buckling behaviour of members with double and mono-symmetric welded I-sections. In one of the first times, the same members are used to test both the stability behaviour and the existing residual stresses. The experimental study is part of a research project founded by DAST (Deutscher Ausschuss für Stahlbau - German Committee for Steel Construction) which is related to the consistent LTB design method "buckling of the compression flange" for ambient and elevated temperatures. The project focuses on the stability behaviour of members with thick plates and steel grades up to S690 and analyses the influence of the welded induced residual stresses. In this context, at the Universität Stuttgart 3-point-bending tests were executed to determine and analyse the lateral torsional buckling behaviour of this members. The residual stresses were measured with two different methods, the sectioning method and X-ray photographic method, at the Ruhr-Universität Bochum. The paper presents the load-deformation behaviour, as well as the ultimate capacities of the tested members. In addition it figures the size and distribution of the residual stresses and the comparison with existing residual stress approaches. Finally, the measured residual stresses are implemented in a numerical model for a nonlinear calculation of the lateral torsional buckling behaviour. The comparison between the experimental and numerical load-deformation behaviour showed only slight differences.

2:30 pm - 2:45 pm

Buckling resistance of mono-symmetric I-/H-section members in biaxial bending, axial compression, and torsion

Bours, Anna-Lena; Winkler, Rebekka; Knobloch, Markus

Ruhr-Universität Bochum, Institute of Steel, Lightweight and Composite Construction, Germany

Keywords: member stability, combined loading

This paper addresses the stability behaviour of simply supported steel members with mono symmetric I-/H-sections in bending, axial compression and torsion. The scope of the current beam-column rules and interaction formulae of EN 1993-1-1:2005 are extended based on the results of a comprehensive numerical simulation study. As part of a parameter study, the effects of the steel grade, the member slenderness ratio, the lz,fl,min/lz,fl-ratio, the load case and the bending moment distribution on the member stability behaviour were analysed. The paper compares the numerically determined member capacities with the results

of the proposed design rules. The results of the simplified rules are conservative. Large deviations arise for the members with semi-compact cross sections, for members subjected to high bending moments about the weak axis and high warping moments and for members with bending moment distributions with changing signs. To reduce the scatter and to optimize the design method different approaches were developed and its accuracy was improved.

2:45 pm - 3:00 pm

Assumption of imperfections for the LTB-design of members based on EN 1993-1-1

Stroetmann, Richard; Fominow, Sergei
Technical University of Dresden, Germany
Keywords: lateral trosional buckling; global analysis; member imperfections

For the stability assessment of members and structures according to EN 1993-1-1 the equivalent member method, the geometrical nonlinear calculation with equivalent geometrical imperfections or the GMNIA analysis with geometrical imperfections and residual stresses can used alternatively. The second possibility requires a corresponding model for the cross section resistance. Depending on the cross section class it has to distinguish between stress related designs (elastic section interactions), the linear or nonlinear plastic section interactions.

For the buckling verification of members and structures, in EN 1993-1-1 alternatively sway and bow imperfections of members as well as scaled buckling shapes of structures may be assumed. The last possibility is used for more complex structures by considering the first and further buckling modes, as relevant. For the verification of lateral torsional buckling, bow imperfections e0 out of plane are defined, which lead in combination with the given loading in the plane and the geometrical non-linear analysis to bending Mz and torsion of the members.

The amplitudes of the imperfections are highly dependent on the nature of the approach (e.g., scaling of the buckling shape, assumption of bow imperfections) and the resistance model for the members. The specifications of the equivalent geometrical imperfections in EN 1993-1-1 were carried out on different bases. In addition to measurements at members and structures and the recalculation from experimental verified buckling curves, the specifications were based on comparisons with results of geometrical and material non-linear analysis.

The results of parameter studies show the way forward for calibrating imperfections for a standardization proposal based on EN1993-1-1. After determining the type of imperfections and the design models for the cross-section resistance, a comprehensive parameter study will shown, which is based on the GMNIA. The influences of the cross sections, the loads as well

as the yield strength will be analyzed. The evaluation of the data in combination with the necessary simplifications for the design practice leads to corresponding definitions of imperfection values e0 and the necessary differentiations.

3:00 pm - 3:15 pm

Stability interaction effects in 3D steel frames – a case study

Snijder, Bert[1]; Titulaer, Luuk[2]; Teeuwen, Paul[3]; Hofmeyer, Herm[1]
[1]Eindhoven University of Technology, The Netherlands; [2]Ballast-Nedam, The Netherlands; [3]Witteveen+Bos, The Netherlands
Keywords: Interaction, 3D, Frames, Eurocode, Design rules, Failure load, FEM, GMNIA

In practice, 3D steel frames loaded in three directions are usually analysed by assessing the different columns and beams separately using the design rules of EN 1993-1-1 (Eurocode 3). The force distribution in the 3D steel frame is then determined first, followed by subsequent cross-sectional resistance checks and member stability checks. The load can be increased till one of the checks is violated thus obtaining the failure load of the frame: Fult,EC. Using the finite element method (FEM) these 3D steel frames can also be analysed (A) as a whole taking material (M) and geometric (G) non-linearity (N) into account and imperfections (I), resulting in an assessment by GMNIA. In this way the failure load can be obtained also: Fult,GMNIA. The first approach is usually expected to be conservative in terms of failure load compared to the more sophisticated second approach. However, in the first approach it is not obvious that all 3D instability effects are covered. Especially if two or more members fail simultaneously by instability and plasticity, interaction effects may cause the 3D frame to have a lower failure load Fult,GMNIA than Fult,EC. This would mean that for such a 3D frame the design rules would not be sufficiently conservative. A research project was carried out to try to find these cases. The paper presents the results of a case study where interaction effects are present and compares different analysis strategies resulting in different failure loads.

3:15 pm - 3:30 pm

Simplified method for lateral torsional buckling of beams with lateral restraints

Beyer, André; Bureau, Alain
CTICM, France
Keywords: lateral torsional buckling, stability

The proposed paper discusses the simplified method for the lateral torsional buckling design of I shaped members with lateral restraints. This popular method, also adopted in Eurocode 3 Part 1-1, consists in verifying the resistance of the compressed "flange" of the member subjected to major axis bending. In this case, the compressed flange of the member is fictitiously composed of the flange itself and 1/3 of the compressed part of the web.

The paper resumes first the analytical derivation of the simplified method and its key assumptions. Then, it presents certain inconsistencies arising if the simplified method is compared to the more general applicable design methods for lateral torsional buckling proposed in Eurocode 3 Part 1-1. In the last part of the paper, the authors propose slight modifications of the method in order to eliminate the mentioned inconsistencies. These modifications are derived analytically and they are validated by numerical simulations.

PI3: Shells

Time: Thursday, 12/Sep/2019: 4:00 pm - 5:30 pm · Location: C206
Session Chair: Rodrigo de Moura Gonçalves, NOVA University Lisbon
Session Chair: Kikuo Ikarashi, Tokyo Institute of Technology

4:00 pm - 4:15 pm

Stability of axially compressed cylindrical shells made of stainless steel for different imperfection patterns

Stranghöner, Natalie; Azizi, Esmaeil
University of Duisburg-Essen, Germany
Keywords: Axially compressed shells, stainless steel, nonlinear material behaviour, degree of material nonlinearity, elastic–plastic buckling, imperfection pattern, stability

The major difference between shells made of carbon steel and those made of stainless steel is the nonlinear material stress-strain relationship of stainless steels below the 0.2% proof stress whereas carbon steel shows a typically linear elastic behaviour up to the yield stress. This nonlinear stress-strain behaviour of stainless steel has a negative effect on the buckling resistance of medium slender shells which has to be considered in the buckling design. In principle, it is necessary to determine the effect of the material nonlinearity in order to ensure a safe and economical design for all stainless steel types of EN 1993-1-4. Furthermore, the shape of the imperfection has an influence on the buckling resistance. For these reasons, extensive finite element investigations have been carried out verified by experimental tests of axially loaded shells. Hereby, the parameters material nonlinearity (for austenitic, duplex and ferritic stainless steels) and imperfection pattern (single inward and multiwave) have been varied. This paper presents the results of this parameter study.

4:15 pm - 4:30 pm

Axial buckling behavior of welded ring-stiffened shells

Jäger-Cañás, Andreas[1]; Li, Zheng[2]; Pasternak, Hartmut[2]
[1]EHS beratende Ingenieure für Bauwesen GmbH; [2]Brandenburg University of Technology
Keywords: shell, axial buckling, ring stiffener

Ring-stiffened flatbed tanks are widely used in many industries for the storage of liquids, such as oil, fertilizers, water, sewage and sludge. For rather medium thin shells, in the range of radius to thickness (r/t) starting from 500 and up to 3000, welding is the most common construction principle. Unavoidably, imperfections due to different cooling speeds and restraints of the plates arise and have an effect on the buckling behavior of those structures.

While nowadays many phenomena regarding unstiffened cylindrical shells, which are axially compressed, are quite well understood, this is not true for ring-stiffened shells. It has been previously shown that the ring stiffeners may greatly

enhance the axial buckling capacity, mostly depending on their cross-sectional area. However, the studies conducted mostly aimed at very thin-walled shells with r/t ratios up to 10000 and employed eigenform-affine substitute imperfections.

For this numerical study, special attention is drawn on the r/t range, which is typical for welded storage tanks and ranges from r/t = 500 up to 3000. Based on a study of the unstiffened shell with a single weld imperfection, the change of buckling capacity with arbitrary spaced welds along the meridian is explored for different r/t-ratios and imperfection depths. A comparison to previously determined results using eigenform-affine imperfections is briefly made. The outcomes of the consecutive study, which focusses on arbitrary ring-stiffened shells, are then presented. Basic parameters, such as r/t and the imperfection depth are chosen accordingly to the unstiffened shell to allow to draw conclusions regarding the enhancement, in both, buckling capacity and behavior, which may be achieved, when ring-stiffeners are employed in the design of axially compressed cylindrical shells.

4:30 pm - 4:45 pm

Buckling Assessment of Cylindrical Steel Tanks with Top Stiffening Ring under Wind Loading

Zeybek, Özer[1,2]; Topkaya, Cem[1]

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Keywords: Storage tanks; Stiffening ring; Buckling, Wind pressure

A stiffening ring is commonly used at the top of the tank wall to increase its strength against external pressure instability. Traditional design treatments generally consider cylindrical storage tanks under uniform external pressure for sizing of the top ring. However, cylindrical steel tanks under non-uniform wind loading have rather different and complex buckling behaviour from those of tanks subjected to uniform external wind loading. In this study, the buckling resistance of the cylindrical steel storage tanks with top stiffening ring under wind loading is investigated using finite element analyses. The changes in the buckling capacity are studied in light of the proposed stiffness ratio for a particular harmonic of wind loading. The results revealed that the changes in the buckling capacity are closely related to the shell-top ring stiffness ratio. Furthermore, a generalized solution that shows buckling pressure ratio ($q_{cr,w}/q_{cr,D}$) is then developed.

4:45 pm - 5:00 pm

Stability of ring stiffened steel liners under external pressure – Comparison of the existing design concept with 3D-FEM analysis

Ecker, Alexander; Unterweger, Harald
Graz University of Technology, Austria
Keywords: External pressure, steel liners, buckling, ring stiffener

External pressure is often the decisive load case for the empty hydraulic pressure tunnel for calculation of the wall thickness of the steel liner. Due to large diameters and thin wall thicknesses the steel liner is susceptible to shell buckling under external pressure. Therefore, the steel liner is often stiffened with rings with a rectangular cross section. In the Sixties of the last century comprehensive research activities started, including tests, and analytical formulae were developed for the design. In basically, these formulae were used nowadays for the dimensioning of the ring stiffened steel liner. This paper deals with the nowadays used analytical design concept for ring stiffened steel liners and the comparison with a comprehensive 3D-FEM analysis. This design concept is very complex and not easy to handle. Two different verifications for buckling of the ring stiffener and the cylindrical shell between the rings are necessary. The combined buckling of the ring and the cylindrical shell between the rings can only be performed with a 3D-FEM analysis. This paper sums up the analytical design concept and the results of a comprehensive comparison with the 3D-FEM analysis are shown, based on steel liner geometries used in practice with varying the distance of stiffeners. Due to the lack of accuracy of the analytic design model a short overview of a potential new design concept using the results of the numerical analysis is shown.

5:00 pm - 5:15 pm

Ultimate shear resistance of cylindrically curved steel panels

Ljubinkovic, Filip; Martins, João Pedro; Gervásio, Helena; Simões da Silva, Luís
ISISE, Portugal
Keywords: cylindrically curved steel panels, elastic critical stress, ultimate shear resistance, edge constraints, FEM

In this paper, a comprehensive numerical study is performed with the aim to investigate the buckling and the post-buckling behavior of simply supported cylindrically curved steel panels subjected to pure shear. The main objective is to understand the influence of geo-metrical parameters, such as curvature and aspect ratio, on the elastic critical load and the ultimate shear resistance. Moreover, a new set of formulae are proposed, which enable simple and accurate prediction of the shear buckling coefficient and the ultimate shear reduction factor for curved panels with curvature parameter and aspect ratio within the ranges of practical interest. The proposed formulae have a form similar to the one available in EN 1993-1-5 (2006) for the prediction of the ultimate shear load of a flat panel.

5:15 pm - 5:30 pm

Accurate and efficient a-posteriori account of geometrical imperfections in Koiter for elastic solid-like shells

Garcea, Giovanni; Liguori, Francesco; Magisano, Domenico; Leonetti, Leonardo

UNICAL, Italy

Keywords: Koiter FE method, geometrical imperfections, post-buckling, limit load, imperfection sensitivity, finite elements.

Thin-walled beams and shells are commonly used as primary components in structure engineering, due to their high specific strength and stiffness, which allow weight and material economy. Their load-carrying capabilities are often determined by buckling, which often occurs for loads much lower than the failure loads of materials.

As a consequence of modal buckling interaction, shell-like structures may exhibit a very unstable post-buckling behavior and may be highly sensitive to initial imperfections, especially to geometrical imperfections. In light of this an imperfection sensitivity analysis becomes mandatory. It consists in seeking the so called worst (detrimental) imperfection cases, which are the shapes of the geometrical imperfections associated with the minimum limit load (safety factor).

The Koiter method recovers the equilibrium path of an elastic structure using a reduced model, obtained by means of a quadratic asymptotic expansion of the finite element model. Its main feature is the possibility of efficiently performing sensitivity analysis by including a-posteriori the effects of the imperfections in the reduced non-linear equations. This work enlarges the validity of the method to a wider range of practical problems through a new approach, which accurately takes into account the imperfection without losing the benefits of the a-posteriori treatment. A mixed solid-shell finite element is used to build the discrete model exploiting the non-linear Cauchy continuum based on a Green strain measure. In this way, adopting the mixed Hellinger-Reissner variational formulation, the strain energy has a 3rd order only polynomial dependence on the FE DOFs with the zeroing of all the fourth order strain energy variations. The resulting asymptotic formulation appears accurate, efficient and simple.

TC8_3: Session of ECCS TC8 - 3

Time: Thursday, 12/Sep/2019: 4:00 pm - 5:30 pm · Location: C202
Session Chair: Bert Snijder, Eindhoven University of Technology
Session Chair: Dinar Camotim, Instituto Superior Técnico, University of Lisbon

4:00 pm - 4:15 pm

Proposal of a design curve for the overall resistance of hollow section members

Toffolon, Andrea; Taras, Andreas
Bundeswehr University Munich, Germany
Keywords: local buckling, overall buckling resistance, rectangular hollow sections, OIC, high-strength steel

The lack of knowledge on the local and local+global buckling behaviour of slender square (SHS) and rectangular (RHS) hollow-sections is currently hindering the construction sector from a wider application of high-strength steel (HSS) and slender hollow sections.

Eurocode and other design provisions define class 4 at a cross-section slenderness > 42ε (compression only) with ε2=235/fy. Thus, a significant number of SHS and RHS with fy ≥ 690 MPa – both cold formed and hot-finished – are considered to be slender and consequently penalized. Besides that, the classification approach itself presents discontinuities in the estimation of the buckling reduction factor, whereas a design curve ranging from the plastic to the slender range would be more efficient and cost-effective both for steel producers and designers.

This paper discusses the results of an extensive numerical campaign, showing that the Eurocode 3 classification is too conservative in the case of SHS and RHS. The local buckling and local+global buckling behaviour will be analysed through an extensive parametric FEM-model study. The gathered data are collated, and the resulting design curve is a proposal for the determination of an overall buckling reduction factor for the determination of the member resistance.

The study represents one of the steps of the RFCS research project "HOLLOSSTAB", during which new design rules for HSS hollow sections are developed on the basis of an "Overall Interaction Concept" (OIC). This concept – similarly to the Direct Strength Method (DSM) used in North America for the design of cold-formed steel open cross-sections – makes use of the results of (numerical) linear buckling analyses (LBA) for the whole member to determine the slenderness and consequently an overall buckling reduction factor. The paper discusses the effectiveness of this approach in the general framework of buckling design checks for hollow sections, discusses existing rules and their implications, shows the numerical campaign results and introduces overall design formulas based on the overall buckling resistance approach.

4:15 pm - 4:30 pm

A Comparative Analysis on the Stability and Ultimate Strength of Steel Plated Girders with Planar and Corrugated Webs

Gonzalez, Alejandro; Vallelado, Lazaro; Serna, Miguel Ángel
University of Cantabria, Spain
Keywords: plated structures, corrugated web

Steel plated girders with corrugated webs has been introduced in the industry with the goal of taking the most advantage of the material capacities in an efficient way. Structural Engineers have realized that folds in the web act as stiffeners, providing sufficient support to avoid the web shear buckling with less material than in the traditional steel plated girders with planar webs. In this context, the paper presents a study on the buckling loads and ultimate strength of plated girders with trapezoidal corrugated webs and results are compared with those obtained for girders with planar webs, with or without stiffeners. The comparative analysis is focused on three main points: local buckling of the web due to shear forces; ultimate strength of the girder under shear forces and bending moments; and global stiffness and ductility behavior. Results show that corrugated webs provides a significant increase in shear buckling resistance when compare with planar plates of the same thickness. However, corrugated webs are prone to fragile post buckling behavior. On the other hand, planar webs develop membrane stresses and provide a more ductile collapse.

4:30 pm - 4:45 pm

Validation of the Overall Stability Design Methods (OSDM) for tapered members

Szalai, József[1]; Papp, Ferenc[2]; Hajdú, Gábor[2]
[1]ConSteel Solutions Ltd., Hungary; [2]Széchenyi István University
Keywords: tapered members, linear buckling analysis, Overall Imperfection Method, Overall Reduction Factor Method

Two new stability design methods are demonstrated and validated: the Overall Strength Reduction Method (OSRM) and the Overall Imperfection Method (OIM). Both methods are based on the linear buckling analysis (LBA) of global structural models and use the standard reduction curves. The OSRM is formulated in the classic way using generalized slenderness and reduction factors while the OIM uses equivalent amplitude for the buckling mode based geometrical imperfection. These new design methods cover all types of buckling modes (flexural, torsional, flexural-torsional, lateral-torsional or any interaction), which can be calculated by LBA of structural models composed of uniform or non-uniform members with arbitrary cross-sections and support conditions and subjected to any complex loading (e.g. biaxial bending with moment gradient, direct torsion effects etc.). There is no need for any additional input for the calculations (like effective length factors, unrestrained lengths of beams, moment gradient factors, equivalent length for the imperfection amplitude etc.) since all the necessary information is received from the elastic critical load and buckling mode shape. This paper clarifies the mechanical interpretation and

proper calculation of all the components of the two methods in case of tapered members with arbitrary support conditions. The validation is performed on a large set of GMNIA results for several different buckling situations of realistic tapered members proving the exceptional accuracy and efficiency of the OSDM.

4:45 pm - 5:00 pm

Sensitivity of the Stiffness Reduction Model Used to Analyze the Ultimate Load Condition of Steel Frames

Rosson, Barry[1]; Ziemian, Ronald[2]; Villalon-Camacho, Teresa[1]; Gurneian, Harout[1]

[1]Florida Atlantic University, United States of America; [2]Bucknell University, United States of America

Keywords: stiffness reduction, inelastic, analysis, ultimate load, failure mode

The stiffness reduction of compact wide-flange steel shapes with an ECCS residual stress pattern was studied using a detailed fiber element model. For a given moment, axial load and residual stress ratio, the reduced stiffness conditions were evaluated and used to develop a new inelastic material model. Ultimate load analyses were conducted on three benchmark frames using the new model and other material models from the literature, and the results were compared with those from advanced nonlinear finite element models. Discussion is given regarding the material models and their ability to match the ultimate load capacity results

5:00 pm - 5:15 pm

Improve load capacity calculations by considering realistic weld imperfections for plates and shells

Stapelfeld, Christoph; Launert, Benjamin; Pasternak, Hartmut; Doynov, Nikolay; Michailov, Vesselin
Brandenburg University of Technology, Germany
Keywords: imperfections, welding, load capacity calculation, stresses, strains, weld imperfections

The topic of this paper is the application of an analytical numerical hybrid model for a realistic prediction of weld imperfections. At the beginning, the analytical model, its physical basis as well as the physical interrelationships are explained. This is followed by the explanation of the coupling procedure between the analytical model and the numerical calculation. The significance of this approach is proven by an application on a large welded structure with several welds and a comparison of the calculated distortions with measurements. Afterwards, the hybrid model is applied on the investigated stiffened structure for the determination of the weld imperfections. An ultimate load analysis gives information about the load carrying behavior under axial loading. The results are compared with the results of ultimate load analysis from a literature example assuming different eigenvalues and scaling. The comparison underlines the potential additional utilization of load bearing capacity by this new approach

5:15 pm - 5:30 pm

Buckling Analysis of Circular Arches with Trapezoidal Corrugated Web

Ibañez, Jose R.; Diez, Rafael; Lopez, Claudio; Serna, Miguel Ángel
University of Cantabria, Spain
Keywords: member stability, arched member

Circular arches with open I cross section may be produced by curving steel profiles. When due to cross section dimensions the curving process is no possible or costly efficient, the arch morphology is obtained by cutting a curved web that is welded to curved flanges. An alternative solution to bending or cutting is to use corrugated webs. Since, due to its geometry, corrugated plates have almost no rigidity to axial forces, a long rectangular corrugated plate may be easily curved and used as web for welded arches, with no material lost as is the case when using cutting process for planar curved webs. The paper presents a study on the stability of circular arches with trapezoidal corrugated webs. In plane and out of plane global buckling loads and buckling shapes are presented and compared with those obtained for equivalent arches with planar webs. Results show the significant impact of this arch morphology on the lateral torsional buckling loads due to the torsional rigidity provided by the corrugated web. Additionally, local buckling improvement due to the use of corrugated web is considered.

Plenary session

Time: Friday, 13/Sep/2019: 8:30 am - 10:00 am · Location: B286
Session Chair: E. Mirambell, Universitat Politècnica de Catalunya-BarcelonaTech
Session Chair: P. Vila Real, University of Aveiro

8:30 am - 8:45 am

On the GNI analysis of simple thin-walled beams with using linear buckling mode as geometric imperfection

Muhammad Ziad, Haffar; Mohammed Hussein, Taher; Adany, Sandor
Budapest University of Technology and Economics, Hungary
Keywords: lateral-torsional buckling, non-principal-axis bending, GNI analysis

When a beam is subjected to non-principal-axis bending, it is usual to decompose the moment into principal-axis components and then to superpose the behavior from the results of the principal-axis cases. For linear analyses the approach of superposition is theoretically correct, but in case of nonlinear analyses, such as lateral-torsional buckling (LTB) or geometrically nonlinear analysis with initial imperfections (GNI), this approach is theoretically questionable. However, it is also possible to solve the non-principal-axis bending directly. Analytical solution of LTB for non-principal-axis bending exists, at least for simple cases (i.e., uniform beam, uniform loading, fork supports). Similarly, it is possible to find analytical solution for the GNI analysis, at least with some simplifications.

In the paper analytical solution for LTB in the case of non-principal axis bending is briefly discussed, then analytical and numerical (i.e., shell finite element) solutions for the GNI analyses are shown. Depending on the initial assumptions, the results of the GNI analyses might be found to be very diverse. The differences are highlighted and briefly discussed in the paper. The results lead to conclusions on the applicability of buckled shapes as initial geometric imperfections.

8:45 am - 9:00 am

Calibration of European web-crippling equations for cross-sections with one web

Misiek, Thomas[1]; **Belica, Andrej**[2]
[1]Breinlinger Ingenieure, Germany; [2]ASTRON BUILDINGS S.A., Luxemburg
Keywords: web crippling, EN 1993-1-3, AISI, cold formed steel

Current design equations given in EN 1993-1-3 for calculating the web-crippling resistance of cross-sections with one web were copied from AISI's Specification for the design of cold-formed steel structural members, taking into account the deviating safety concepts: The load and resistance factor design (LRFD), with resistance factors fw applied on nominal values, and the limit state design with partial factors gM applied on characteristic values as defined in EN 1990. Furthermore, the webcrippling equations of subsequent editions of AISI's Specifications (then designated AISI S100) were completely revised based on the web-crippling data collected and evaluation done by Beshara and Schuster.The paper presents the results of a calibration of a generalized web-crippling equation to be used for cross-sections with one web (i.e. C- and Z-sections). In addition, some special applications for built-up cross I-sections made of two Csections and for nested Z-sections and fastening of C- and Z-sections with cleats but without gap between the lower flange and the supporting structure are considered. The constant factors of the generalized web-crippling equation were calibrated to comply with the safety concept described in EN 1990, taking into account EN 1990, Annex D, and a partial factor γM1 = 1.1. That way the paper gives an introduction as well as background information on proposed changes and amendments in EN 1993-1-3.

9:00 am - 9:15 am

The capacity of bolted cold-formed steel connections in bending

Mojtabaei, Seyed Mohammad; Becque, Jurgen; Hajirasouliha, Iman
The University of Sheffield, United Kingdom
Keywords: cold-formed steel sections; bolted moment connection; FE analysis; design equation

Cold-formed steel (CFS) sections find extensive use in moment-resisting portal frames, which are commonly encountered in industrial buildings. The structural performance of a moment-resisting portal frame, however, depends significantly on the behaviour of the column-to-rafter connections. This paper investigates the capacity of these connections, which are commonly implemented with a gusset plate bolted to the webs of back-to-back channel sections, when subjected to a pure bending moment. Detailed Finite Element (FE) models, accounting for material non-linearity, geometric imperfections and realistic bolt behaviour were developed using the ABAQUS software and were validated against experiments on bolted CFS apex connections. Using the validated model parametric studies were carried out to investigate the effects of the cross-sectional dimensions and thickness of the connected members, the bolt group length and the geometric arrangement of the bolts in the connection. On the basis of this data a design equation was proposed which accounts for local buckling of the CFS beam web adjacent to the first bolt row as the dominant failure mode.

9:15 am - 9:30 am

Tests and Design of Built-up Section Columns

Phan, Dang Khoa; Rasmussen, Kim J.R.
The University of Sydney, Australia
Keywords: Cold-formed steel, Built-up, Column, Buckling, Screw

Built-up sections are increasing in popularity as structural elements in the cold-formed steel (CFS) industry. They are composed of two or more component sections connected by discrete fasteners, most commonly screws or bolts, typically spaced evenly along the length. Conventionally, two singly symmetric sections are connected to form a doubly symmetric cross-section. However, this study focuses on sections formed by three or more lipped channel C-sections,

which are being used more frequently in recent years. The paper details an experimental investigation of the strength and behaviour of screw-fastened built-up columns with variable lengths. The cross-section configurations include singly-symmetric columns composed of three channel sections (3C), for which the failure mode was either local, distortional and/or flexural-torsional modes, and doubly-symmetric columns formed by four sections (4C) which failed in local and/or flexural buckling modes.

9:30 am - 9:45 am

Experimental study on the general behaviour of stainless steel frames

Arrayago, Itsaso; Real, Esther; Mirambell, Enrique; González de León, Isabel

Universitat Politècnica de Catalunya, Spain

Keywords: Stainless Steel, Frames, Experimental tests

Mechanical properties such as high ductility, adequate toughness, considerable strain-hardening and good fire resistance make stainless steel an excellent construction material for structures required to withstand accidental loading due to seismic and/or fire events. In recent years, a considerable amount of research has been devoted to the understanding of the structural performance of single isolated stainless steel members. Notwithstanding, advances related to the analysis of more complex stainless steel structures, such as frames, are scarce. As a matter of fact, EN1993-1-4 does not establish specific design rules associated with the global analysis of stainless steel frames and thus, provisions given for carbon steel need to be adopted. The lack of guidance on plastic design in general and design of frames in particular, is an obstacle to the optimal design of stainless steel structures given the remarkable differences in their behavior compared with carbon steel.

An extensive experimental program on sway and non-sway austenitic stainless steel frames with slender and stocky rectangular hollow sections is being carried out at the laboratory of the Department of Civil and Environmental Engineering "Luis Agulló" of the Universitat Politècnica de Catalunya, to assess the performance of stainless steel frames subjected to static loading.

The objective of this paper is to present the tests on austenitic stainless steel non-sway and sway frames and to investigate the effect of the material and geometric nonlinearities and strain hardening in their overall performance, to assess existing design rules in terms of predicted ultimate capacities and second order effects.

CFS3: Cold formed steel, built-up members

Time: Friday, 13/Sep/2019: 10:30 am - 12:15 pm · Location: C202
Session Chair: Kim J.R. Rasmussen, University of Sydney
Session Chair: Jelena Dobrić, University of Belgrade Faculty of Civil Engineering

10:30 am - 10:45 am

Buckling of Spatial Laced Columns Composed of Built-Up Cold-Formed Steel Channel Members

Bastos, Cristiane Cruxen Daemon D Oliveira; Batista, Eduardo de Miranda
Federal University of Rio de Janeiro - COPPE, Brazil
Keywords: Laced built-up columns, Cold-formed steel structures, Buckling, Elastic critical load, Built-up sections

Spatial laced columns, composed of cold-formed steel (CFS) members are usually applied in industrial buildings, offering advantages of lightness, fast production, easy transportation and erection. The main design standards do not present methods for designing this type of CFS structural system. From the literature, we verify tests on spatial built-up columns are limited. This paper presents results of full-scale experimental tests carried out in spatial laced built-up columns, designed with lipped channel CFS members. The five tested spatial laced columns have respectively 6, 12 and 16m length and 0.8 and 1.25mm plate thickness, with 400x400mm cross section.

The laced column chords, composed of two lipped channel members connected with self-drilling screws, were previously analyzed with the help of both Generalized Beam Theory and Finite Element Method with thin shell elements (FEM), in order to identify its buckling loads and modes. The results of experimental tests are reported, conducted on built-up CFS lipped channel members, 480mm length and 0.8mm thickness, to evaluate axial compression behavior of the chord, with different number of screws and end conditions. The axially compressed built-up members displayed local buckling, non-composite behavior and minor effect of number of screws.

For the built-up column as a whole, elastic buckling and nonlinear FEM analyses were performed with 3D bar elements. Four analytical methods were applied to obtain global buckling load including shear effect, for pin-ended condition. The results indicate quite similar critical elastic buckling loads and good agreement with those from the FEM buckling analyses. The collapse mechanism of 6m length columns was typical squash-load and global buckling developed for 12 and 16m length columns. The obtained results indicated the tested columns perform low influence of shear effect and critical buckling load may be accessed with the help of available analytical equations.

10:45 am - 11:00 am

The influence of stiffeners width on buckling modes of steel LC-beams subjected to bending

Kubiak, Tomasz; Kolakowski, Zbigniew; Kazmierczyk, Filip
Lodz University of Technology, Poland
Keywords: thin-walled beams, interactive buckling, postbuckling behaviour

In the present paper the influence of the stiffener's width on buckling mode of lipped section steel beams have been analysed. Additionally, different wall thickness of the lip-channel section beams was considered. During calculation all type of buckling mode were determined i.e. global, local, distortional, lateral, torsional and coupling form of previously mentioned. The beams under consideration were subjected to bending in the web plane. A plate model (2D) was adopted for lipped section beams. The shear lag phenomenon and distortional deformations were taken into account. The beams were assumed to be simply supported at the ends. A method of the modal solution using the analytical-numerical method (ANM) and the transition matrix method, was applied. LC-beams, from short through through medium-length to long beams have been examined. The special attention have been paid for internal forces correspond to different buckling modes. It has been noticed that the internal forces have the great influence on coefficient describing the postbuckling equilibrium paths. The results obtained by developed analytical-numerical method based on asymptotic Koiter theory have been verified by results obtained by FEM calculations.

11:00 am - 11:15 am

Numerical investigation of built-up cold-formed steel beams with corrugated web

Ungureanu, Viorel[1]; Lukačević, Ivan[2]; Both, Ioan[1]; Burca, Mircea[1]; Dubina, Dan[1]
[1]Politehnica University of Timisoara, Romania; [2]University of Zagreb, Zagreb, Croatia
Keywords: Corrugated web beams, thin-walled cold-formed, spot welding, numerical investigations

Built-up corrugated web beams (CWB) represent an assembly of multiple cold-formed steel components of various thicknesses connected by means of screws or welding. Recently, tests on such built-up beams have been performed within the CEMSIG Research Center of the Politehnica University of Timisoara, in which the connections between the components were made by spot welding. Following the validation of the numerical model, the paper investigates the influence of several parameters, i.e.: the thickness of the flanges, the thickness of the cor-rugated web, the thickness of the shear panel, the magnitude of the initial imperfections and the number and position of the spot welds. The parametric study was conducted on a beam with the same global dimensions as the tested one.

11:15 am - 11:30 am

Global buckling strength of built-up cold formed steel columns under compression

Kobashi, Tomoki; Shimizu, Nobutaka
Nippon Steel Corporation, Japan
Keywords: built-up member, lipped channel, global buckling, stud

The built-up members are widely used for the studs and joists of the thin-walled structures. These built-up members can expect higher global buckling strength than the single member because the members which comprise the built-up column section restrain their flexural buckling each other. This capacity increase is a well-known result and the current design code provides design equations to modify the slenderness ratio of built-up members. However, the design equation is highly simplified. Thus, it is available only for the buck-to-buck lipped channel and cannot apply for the other built-up sections.

The objective of this research is to provide a design formula for the flexural buckling strength of built-up members, which can evaluate not only for the buck-to-buck lipped C section members but also for the other doubly symmetric built-up section members. In this research, the flexural buckling strength of four different section types was investigated. We regard these members as a two-layer composite member and obtained a design equation for their flexural buckling strength. Through the eigenvalue analysis, we found that the suggested method agreed well with the numerical analysis results. In addition, we conducted elasto-plastic FE analysis to investigate the inelastic buckling strength (i.e. maximum strength) of the built-up members. Through numerical investigations, we found that the nominal strength which evaluated its flexural buckling strength by proposed equations agreed well with the maximum strength by FE analyses.

11:30 am - 11:45 am

Built-up cold-formed steel beams with web openings

Ungureanu, Viorel[1]; Both, Ioan[1]; Calin, Neagu[1]; Burca, Mircea[1]; Dubina, Dan[1]; Cristian, Antonio Andrei[2]

[1]Politehnica University of Timisoara, Romania; [2]Technical University of Civil Engineering of Bucharest, Romania

Keywords: spot welding, MIG brazing, thin-walled cold-formed steel

Cold-formed steel profiles are lightweight elements which can be assembled in a numerous variety of shapes considering either truss structures or corrugated web beams. Especially in residential or office buildings, adjustments are required for the service installations. The web openings represent a weak point in a beam and special attention must be considered to maintain the initial capacity. Previous experimental tests were performed on built-up beams with lipped channel sections as flanges and trapezoidal corrugated steel sheets as web. The connection of the beam components was performed by two methods, i.e. resistance spot welding and MIG brazing. The paper presents the experimental investigations on two full scale beams with strengthening solutions for the web openings, function of the welding technique, i.e. a reinforcing steel plate was spot welded to the corrugation of the web and a border type frame was MIG brazed on the opening perimeter. A lesser influence of the web opening was observed for the beam connected by MIG brazing as a superior bearing capacity was obtained.

11:45 am - 12:00 pm

Coupled buckling of steel LC-beams under bending

Kolakowski, Zbigniew; Kubiak, Tomasz; Kamocka, Monika

Lodz University of Technology, Poland

Keywords: Lip-channel section; coupled instability; postbuckling behaviour;

The presented results of performed research are a continuation of the earlier published paper [1], where the influence of secondary global buckling mode on postbuckling behavior for thin-walled beams under bending have been noticed. This paper deals with the interactive buckling of thin-walled lipped channel (LC) beams subjected to bending. In the prebuckling state, the beams were subjected to linearly variable loading resulting in bending in the web plane (i.e., the upper flange was tensioned, the lower one was compressed). A plate model (2D) was adopted for lipped section beams. The shear lag phenomenon and distortional deformations are taken into account. The structures were assumed to be simply supported at the ends. A method of the modal solution to the interactive buckling problem within Koiter's asymptotic theory, using the semi-analytical method (SAM) and the transition matrix method, was applied. Different length of lip channel section beams, from short through medium-long to long, were considered. The special attention was paid on the influence of the effect of the secondary global buckling mode on an interaction between different modes. In the cases under consideration, an influence of the secondary global mode is most evident for medium-length of the beams. It is advisable to

extend this analysis onto an effect of the length of edge reinforcements and the wall thickness of LC-beams on the interactive buckling and load carrying capacity. The results obtained based on semi-analytical method (SAM) were validated by results obtained in FEM.

[1] Kolakowski Z., Jankowski J. Interactive buckling of steel C-beams with different lengths – From short to long beams. Thin-Walled Structures, 125, 2018, 203–210.

12:00 pm - 12:15 pm

Distortional buckling of stiffeners in stainless steel profiled sheeting

Jůza, Jan; Jandera, Michal
Czech Technical University in Prague, Czech Republic
Keywords: distortional buckling; stainless steel; cold-formed steel; stiffener; trapezoidal sheeting

The research presents a numerical study of compressed stainless steel cold-formed thin-walled plates with an intermediate stiffener as is common for flanges of profiled sheeting. The numerical model was validated on tests from literature. These test results were substantially extended by a parametric study to cover the whole slenderness range and common geometries of stiffeners. As stainless steel material exhibits more nonlinear stress-strain behaviour than carbon steels, the results of the numerical study also shown significant deviation of the resistance which is contributed to the material non-linearity. The distortional buckling curve for stainless steel was lower for the whole slenderness range and a modified design procedure was therefore proposed.

Seismicity: Seismic design

Time: Friday, 13/Sep/2019: 10:30 am - 12:15 pm · Location: C206
Session Chair: Luis Calado, ist
Session Chair: Mario D'Aniello, University of Naples Federico II

10:30 am - 10:45 am

Seismic Response of Steel Dual Eccentrically Braced Frames with Equal-Strength Joints

Penelov, Chavdar; Rangelov, Nikolaj
Department of Steel and Timber Structures, UACEG, Sofia, Bulgaria
Keywords: Seismic response, dual systems, steel eccentrically braced frame, joints, nonlinear pushover analysis, incremental dynamic analysis.

Along with the typical structural types of primary earthquake resisting structures, dual systems combining moment resisting frames with concentric or eccentric bracings are quire promising for seismic applications. On the other hand, their response to seismic actions is more complicated and more research is needed in this context.

In this paper, two case studies on dual eccentrically braced frames (moment resisting frame, MRF, plus eccentrically braced frame, EBF) for six- and ten-storey office buildings are presented. Both systems are designed to resist simultaneously the seismic action in the considered direction with high ductility class according to EN 1998-1. The beam-to-column joints are designed both as equal-strength joints according to the classification for performance objectives recently introduced by the European Equaljoints project.

The seismic assessment of the dual structures is performed by adequate nonlinear models for the potential dissipative zones: the beam-to-column joints (end-plate connections and web panels) of the MRF as recommended by the Equaljoints project, and the link elements of the EBF subsystem, using hysteretic constitutive multi-linear model with kinematic strain-hardening. Both nonlinear static pushover analysis and incremental dynamic analysis (IDA) have been carried out to assess the seismic response of the dual system. The results are compared to those obtained by the simple design procedures based on the elastic analysis.

This research is performed within the current Equaljoints Plus project, funded by RFCS of the European Commission.

10:45 am - 11:00 am

Performances of moment resisting frames with slender steel and composite sections in low and moderate seismic areas

Degée, Hervé[1]; Duchêne, Yves[2]; Hoffmeister, Benno[3]
[1]Hasselt University, Belgium; [2]Design Office Greisch, Belgium; [3]RWTH Aachen, Germany
Keywords: Slender steel sections, Slender composite sections, Moment resisting frames, seismic design, low and moderate seismicity

Even in the most advanced seismic design methods like performance-based design, the general philosophy is always based on the assumption of global and fully developed plastic mechanisms whatever the seismicity level, together with the use of corresponding capacity design principles. The aim of the recently completed European research program Meakado was therefore to study design options with requirements proportioned to the actual seismic context of constructions in areas characterized by a low or moderate seismic hazard, contrary to most researches aiming at maximizing the seismic performances. More precisely the objective is to propose design rules that are optimized for the actual seismic action, providing the necessary safety level without imposing excessive requirements, and thus limiting the incremental complexity and costs associated with anti-seismic design.

In this general framework, specific investigations have been carried out regarding typical beam profiles commonly used for steel and composite frames. In a first stage, experimental tests on class-3 and class-4 built up steel profiles and composite beam-to-column nodes were performed. The measurement results were evaluated with regard to the development of the hysteretic behavior with particular emphasis on the cyclic degradation. These test results have been used as reference for the calibration and validation of numerical model aiming at extending the scope of the experimental outcomes through appropriate parametric variations regarding the behavior of nodal connections as well as towards the global analysis and behavior of structures made of class 3 and 4 profiles. Based on the outcomes of these investigations, practical design recommendations are finally derived for moment resisting frames located in low and moderate seismicity regions.

11:00 am - 11:15 am

Beam-to-column joints for slim-floor systems in seismic zones: numerical investigations and experimental program

Vulcu, Cristian; Don, Rafaela; Ciutina, Adrian
Politehnica University of Timisoara, Romania
Keywords: slim-floor; concrete-dowels; moment-resisting beam-to-column joints

The slim-floor building system is attractive to constructors and architects due to the integration of steel beam in the overall height of the floor, which leads to additional floor-to-floor space, used mostly in acquiring additional stories. The concrete slab offers natural fire protection for steel beams, while the use of novel corrugated steel sheeting reduces the concrete volume, and can replace the secondary beams. Currently the slim-floor solutions are applied in non-seismic regions, and there are few studies that consider continuous or semi-continuous fixing of slim-floor beams. The current ongoing study was carried out with the aim to develop reliable end-plate bolted connections for slim-floor beams, that can be applied to buildings located in seismic areas. For this purpose, a numerical program was carried out in two stages: (i) calibration of a FE model based on a four point bending test of a slim-floor beam; (ii) case study performed for the investigation of beam-to-column joints with moment resisting connections between slim-floor beams and columns. The current paper presents the main findings of the study, an overview of the experimental program, the main conclusions and future research activities.

11:15 am - 11:30 am

Seismic design criteria for CFS steel-sheathed shear walls

Campiche, Alessia; Shakeel, Sarmad; Fiorino, Luigi; Landolfo, Raffaele
University of Naples "Federico II", Italy, Italy
Keywords: Shear Walls, Seismic Design, Effective Strip Method

The current European earthquake standard EN1998-1 does not provide the seismic design criteria for cold formed steel (CFS) steel-sheathed shear walls, limiting their use as a lateral force resisting system in lightweight steel buildings. In order to overcome this lack of guidelines, a specific study has been performed to extend the applicability of the Effective Strip Method (ESM), given in North American standard AISI S400 to EN1998-1. The method evaluates the shear resistance of steel-sheathed shear walls and it is permitted only in USA & Mexico as an alternative to tabulated shear resistance for predefined wall configurations. In order to further validate its scope of application, it was applied to additional available experimental results of walls tested in Canada. Only for some configurations, the ESM does not give acceptable predictions. Furthermore, the ESM was applied following the European approach, to make its use possible in context of European seismic design methodology. The overstrength factor for the design of non-dissipative elements was evaluated. Based on the results, it is concluded that the ESM could be appropriate for the evaluation of resistance of steel-sheathed shear walls in Eurocodes.

11:30 am - 11:45 am

A Yielding Criterion for Seismic Gusset Plates in Tension

Elliott, Matthew D.; Teh, Lip H.
University of Wollongong, Australia
Keywords: balanced design procedure, bolted connection, gusset plate, special concentrically braced frame, yielding capacity

Gusset plate yielding has been recognised as a complementary ductile yielding mechanism in the Balanced Design Procedure proposed for special concentrically braced frame (SCBF) connections, formulated at the University of Washington. The seismic design procedure aims to maximise ductile yielding in the frame and therefore the drift capacity of the frame. To achieve the aim, accurate models for determining the yield capacity of relevant components is desirable. In particular, thicker than necessary gusset plates have been found to limit the drift capacity. Based on the authors' previous finding regarding the Whitmore tension capacity of bolted connections, this paper proposes a more rational yielding criterion for bolted gusset plates in tension. It is shown that the new criterion often results in similar design outcomes to the Whitmore yielding criterion, but more importantly provides a consistent and rational procedure for applying the Balanced Design Procedure to the design of a bolted gusset plate in an SCBF system.

11:45 am - 12:00 pm

Cyclic plastic behavior of steel material under uniaxial load paths

Budaházy, Viktor; Dunai, László
Budapest University of Technology and Economics, Hungary
Keywords: Steel material test, cyclic plastic hardening, memory behavior, low-cycle fatigue

The cyclic inelastic response of steel material fundamentally determines the structural behavior of a structures during an earthquake event. The constantly growing demand on ever-accurate design and economy requires the comprehensive knowledge of structural steel behavior, specially under arbitrary large inelastic cyclic loading. Although several study have described the most important component of steel plasticity several behavioral factors are not explored. In this paper, fatigue, hardening and memory behavior of the structural steel were investigated under different loading circumstances with altogether 31 uniaxial load protocols up to 12% strain range. Five different steel materials are investigated from S235 to S420, which cover the most commonly used steel grades in European seismic design practice. Beside the description of the tendencies, quantified variables and empirical equations are presented for the description of hardening and memory behavior of steel material.

As a result of the study, the maximum cyclic stress was significantly larger, than the monotonic ultimate strength, and this additional cyclic hardening develops in relatively small strain range whit in few cycles. The isotropic part of cyclic

hardening depends on the maximum and accumulated plastic strain, and the kinematic hardening is less sensitive for these strain limits. The steel material shows fading type memory behavior, although the effect of the previously experienced load path can only partially be vanished.

12:00 pm - 12:15 pm

Study on the influence of Reduced Beam Sections on the seismic behaviour of a Moment Resisting Frame

Jiménez, Adrià; Mirambell, Enrique; Real, Esther
Universitat Politècnica de Catalunya, Spain
Keywords: Seismic design, moment resisting frame, reduced beam section

This paper presents the results of a series of time history analyses performed in Abaqus on a single-span two-storey moment resisting frame. The aim of this paper is to show a reduction in base shear when the structure is provided with Reduced Beam Sections close to the beam-to-column connections and to confirm that stress concentrations in the beam-to-column welds are avoided. The Reduced Beam Sections adopted have been designed in compliance with EN1998-3. The structure is modelled with shell elements in order to accurately reproduce the formation of plastic hinges in the critical sections of the structure without the need to rely on predefined moment-rotation diagrams. The dynamic analyses are performed by introducing artificial accelerograms at the base of the columns of the structure after the dead loads and live loads have been applied. The accelerograms used in the analyses are obtained from the elastic response spectrum in EN1998-1 in order to reproduce a typical seismic event represented by the spectrum in the Eurocode.

Structures 1: Structures

Time: Friday, 13/Sep/2019: 10:30 am - 12:15 pm · Location: C204
Session Chair: Trayana Tankova, ISISE – Department of Civil Engineering, University of Coimbra
Session Chair: Federico Guarracino, University of Naples "Federico II"

10:30 am - 10:45 am

Modelling of the roof bracing system in single-storey industrial buildings

Zamorowski, Jan[2]; Gremza, Grzegorz[1]
[1]Silesian University of Technology, Poland; [2]The University of Bielsko-Biała, Poland
Keywords: bracings modelling, industrial buildings, imperfections

The rules introduced into the codes EN 1090-2 and EN 1993-1-1 are not fully compatible in the area of modeling of roof bracings in industrial halls and they also do not guarantee reproducing the real behavior of these bracings in the proposed standard calculation model.

The EN 1090-2 standard provisions contains acceptable basic and functional geometric tolerances in the scope of fabrication and assembly of structures, what indicate the possibility of bending deformation of roof trusses in the plan, assuming opposite direction of initial bows of upper and lower chords, what is consistent with the results of measurements made on real structures after their assembling. In turn, computational model proposed in the EN 1993-1-1 reproduces with practical accuracy the behavior of transverse roof bracings in single-bay buildings without vertical bracings. Therefore, the rules contained in EN 1993-1-1 do not fully guarantee the safety of other roof bracing elements.

In available publications many different computational models of roof bracings are presented, in which influences of the geometric imperfections on the effort of the elements of the braced roof are often taken into account twice. For example, into the calculation model of the spatial structure of the roof or the whole hall, standard bow geometrical imperfections of the upper chords of the trusses and additionally horizontal forces resulting from vertical loads and inclination (tilt) of these trusses, in analogy to the P - □ effect in the halls, are introduced.

In this work, on the example of a single-bay and two-bay hall (industrial building) with vertical roof bracings, the results of elastic spatial analysis of the hall with geometric imperfections will be presented, when various calculation models will be used. The obtained results will be referred to the standard calculation model allowing to conclude about deficiencies of this model and indicate the need to verify standard rules in this scope.

10:45 am - 11:00 am

Ultimate bending resistance of pipes: testing arrangements and nonlinear effects

Guarracino, Federico
University of Naples "Federico II", Italy
Keywords: pipes, pipelines, testing arrangement, bending, limit state

The design of submarine pipelines operating in very deep water relies on accurate test results for the local buckling collapse of pipes subjected to bending loading. Several test results have shown apparently anomalous values of axial tensile and compressive strains in comparison to the values that would be expected on the basis of simple bending theory. This fact has important consequences for the efficacy of the design factors derived using experimental results. Examples of anomalous test results are given and the cause of the differences between the strain values obtained in the tests are explained on the basis of nonlinear effects. The ultimate bending resistance of the pipes is then evaluated on the basis of the theorems of Limit Analysis which are applied circumscribing the nonlinear kinematics of the problem.

Conclusions are drawn with respect to limit state for the design of onshore and offshore pipelines.

11:00 am - 11:15 am

Towards automated Identification of Structural Steel Components from 3D-Point Clouds to subsequent GMNA-Stability-Analysis

Merkl, Christian; Taras, Andreas
Bundeswehr University Munich, Institute of Structural Engineering, Germany
Keywords: reverse engineering, computer vision, point clouds, CAD, FEM

Due to the growing computational performance and advancing image-processing capabilities, comprehensive geodetic data acquisition of structures has become possible. Digital inventories of structural components may be performed either through photogrammetry or through laser scanning, and it results in 3D point clouds. Until recently, however, their goal-oriented further processing posed problems for civil engineers in terms of actual information acquisition, data compatibility and data transfer to general CAD or FEM software used in day-to-day practice. Structural engineers require very specific information of individual structural components as well as of their assembly to generate usable, FEM-compatible structural models. In steel construction, for example, this modelling is primarily based on beam and shell elements, which first require the reduction of captured three-dimensional information to surfaces and further to one-dimensional or two-dimensional component descriptions. This paper presents new developments towards automated procedures for these tasks. It presents an algorithmic approach to extracting characteristic geometric information of a selected steel component from its point cloud. For this purpose, point cloud data of channel sections is used. In this data, basic geometric elements, in particular planes and cylinders are automatically

recognised and measured via computer vision tools. Afterwards, the acquired information is transferred to input data for the FE-software ABAQUS. Finally, a numerical study shows the robustness of this procedure.

11:15 am - 11:30 am

Degradation processes in normalised mild- and low-alloy steel building structures in service

Wichtowski, Bernard; Hołowaty, Janusz
West Pomeranian University of Technology Szczecin
Keywords: steel properties, ageing, toughness

A uniform algorithm for assessing the technical condition and capacity of steel structures with a long period of service has yet to be devised. Each case should be treated individually using in-situ diagnostic testing. As explained in the technical literature, no two steels are the same, and even small changes in chemical composition or production parameters may drastically change their properties. This particularly concerns structures built in the 20th century. Advances in metallurgical processes and the invention of different heat treatment methods allowed for a wide range of changes in steel properties. Along with low carbon mild steels, low-alloy steels started to be used in building structures and heat treatment processes were introduced.

The paper presents the results of research on the following normalised steels:

a) St37.12 mild steel, of German origin, from a railway bridge constructed in 1938, and

b) 18G2A low alloy steel, of Polish origin, from the sheeting of five cylindrical tanks constructed in 1973.

Chemical and mechanical tests are described on a range of micro and macro aged and normalised steels from these structures. According to our knowledge, these are probably appropriate ageing tests for such steels. These are the "future tests" according to Eurocode 3 where in building structures, grade S355 normalised or thermo-mechanically rolled steels should be used. The probability for similar material degradation is expected in these steels.

11:30 am - 11:45 am

Crashworthiness performance of tubular energy absorbing structures with triggers

Kotełko, Maria[1]; Ferdynus, Mirosław[2]; Okoń, K.[2]
[1]Lodz University of Technology, Poland; [2]Lublin University of Technology, Poland
Keywords: progressive buckling mechanism, energy absorption capacity, crushing mechanism

The paper presents results of the parametric study into energy absorption capability of thin-walled tubular columns of prismatic cross-section with different types of triggers: cylindrical indentations (redrawing dents) and spherical concave or/and convex indentations ("bumps") of different shape and location. Columns are subjected to axial impact compressive load. Extensive parametric analysis is performed using Finite Element numerical code. Several crashworthiness indicators are examined to asses energy absorption effectiveness of structures under investigation, among them the peak crushing force, which de-creases due to the trigger and this reduction is mostly desirable from biomechanical rea-sons. The FE numerical models and numerical results are validated by means of experimental impact tests performed on the drop hammer rig experimental stand. Conclusions concerning optimal design of examined structures from energy absorption effectiveness point of view are derived.

11:45 am - 12:00 pm

Nonlinear behavior and instability of deployable arches

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Keywords: Deployable structures, arch, multistable structure, snap-through, structural stability

Deployable structures consist of a group of structures capable of modifying their shape and volume in order to meet a range of conditions and needs. They are usually prefabricated structures consisting of straight bars linked together in a compact bundle, which can then be unfolded into large-span, load bearing structural shapes. These structures have dual functionality since they act as mechanisms during its deployment and become structures capable of supporting loads during the service phase. In addition, they should be lightweight and compact to be easily transported and simple and quick to deploy. All these restrictions make it difficult to choose the best parameters regarding the shape and material of the structure, since many analyzes must be performed in order to find parameters that give lowest weight, highest stiffness, and that allow the structure to perform its two functions besides ensure its reuse. Among the types of folding structure, those made of pantographic elements (scissors) have attracted great interest from engineers and architects in recent years. This study evaluates the nonlinear behavior of two two-

dimensional arch structures each constituted by a classic type of pantographic element, namely: polar and translational. For this, a detailed nonlinear analysis is conducted through the Galileo computer program in order to evaluate the influence of structure's geometrical parameters, imperfections and the type of material and element on the nonlinear behavior and stability of the structure. The results obtained by our analyzes reveal, in most cases, an extremely nonlinear behavior of these structures with the nonlinear equilibrium path exhibiting several load and displacement limit points where jumps to remote and undesirable configurations may occur. Based on them, conclusions on the influence of system parameters on the load-carrying capacity of the arch are obtained.

12:00 pm - 12:15 pm

Static effects of modular structures made of containers

Miller, Ondřej[1]; Křivý, Vít[1]; Mikolášek, David[1]; Pařenica, Přemysl[1]; Cuřín, Richard[2]

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Keywords: modular building, load bearing structure, mechanical resistance, stability, container

When designing and static-assessing modular buildings, it is necessary to take into account some specificities and differences related to the static effect of the load-carrying structure made of interconnected steel containers. The objective of container module manufacturers is to achieve a broad application of their products in building construction. The load-carrying structure of containers used in building construction was created by the modification of the original containers used mainly in rail and ship transport. The necessary condition for the application of the products in building construction is to ensure the mechanical resistance and stability of the supporting structure in accordance with the requirements of the applicable standards. This paper therefore points to selected static problems associated with the use of containers when designing multi-storey modular buildings.

CFS4: Cold formed steel

Time: Friday, 13/Sep/2019: 1:45 pm - 3:00 pm · Location: C202
Session Chair: Michal Jandera, Czech Technical University in Prague
Session Chair: Ioan Both, University Politehnica of Timisoara

1:45 pm - 2:00 pm

Failure plastic mechanisms in TWCFS columns under eccentric compression

Kotełko, Maria[2]; Ungureanu, Viorel[1,3]; Dubina, Dan[1,3]
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Keywords: eccentric compression, plastic mechanism, yield line analysis

The paper presents a database of local plastic mechanisms of failure in lipped channel section columns subjected to eccentric compression about minor axis. Selected results of both numerical and experimental validation of developed mechanisms models are presented. Comparative diagrams of equilibrium paths obtained experimentally and from FE simulations together with post-failure curves obtained via yield line analysis, based on developed mechanisms models, are shown. Conclusions concerning the applicability of presented mechanisms models for determination of load-carrying capacity of structures under investigation are derived. Further research perspectives are presented.

2:00 pm - 2:15 pm

Strength characterisation of a CFS section with initial geometric imperfections

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Keywords: cold-formed steel, geometric imperfection, buckling strength, polynomial chaos expansion, metamodelling

The strength of a CFS member gets highly affected by the presence of any geometric imperfection (local or global). Moreover, these imperfections are the major source of uncertainty in the prediction of buckling strength (Pn) of a CFS member. Previous works on strength characterization of CFS members have shown the effects of considering the uncertainty in local imperfection for a member undergoing local buckling. However, the uncertainties imparted due to global imperfection is still not addressed. The prediction of Pn in current design codes is based on some deterministic value of the global imperfection. Considering this, the current paper aims at the statistical characterisation of Pn taking into account uncertainties in both local and global imperfection.

For this reason, a CFS member undergoing local (Type 1) and global (flexural-torsional) buckling is selected. However, the probabilistic assessment of Pn, in conjunction with finite element simulations becomes computationally

expensive. Thus, to address this high computational cost, metamodelling technique approximating the original simulation model with a simplified mathematical model is proposed. Characteristic Pn values are recommended for a selected range of non-dimensional slenderness (λc) and these values are then compared with current design recommendations for Pn. It is observed that at the higher range of non-dimensional slenderness (λc ≥ 1), where the flexural-torsional buckling mode governs the performance of CFS members, the AISI prediction becomes conservative, while at the lower range (λc < 1), the AISI predictions are found to be close to uncertainty analysis based recommendations.

2:15 pm - 2:30 pm

Elastic buckling strength of lipped channel section beams restrained on upper flange subjected to bending

Masuda, Hiroto; Ikarashi, Kikuo
Tokyo Institute of Techonology, Japan
Keywords: LIpped Channel Section, Energy Method, Distortional Buckling

In thin-walled construction, beam or column members are often attached to plane member such as structural plywood. These kind of structures have been introduced recently in Japan. It has been reported that distortional buckling may occur when these structural members are subjected to compression or bending. Of course we have to take buckling problems into account in structural design. However Japanese code for thin-walled construction underestimates allowable stress for distortional buckling, and therefore design formula based on theoretical solution is needed for economical benefits.

In this paper, we propose a closed-form expression of elastic buckling strength corresponding for distortional buckling mode for thin-walled lipped channel section member subjected to bending. We include effects of sectional dimensions, bending moment gradient, support conditions and rotational stiffness provided by plane member. We first performed FEM analyses to understand the overview of buckling behavior. Then we built a model for energy method, which is one of theoretical and effective methods to find what parameter determines elastic buckling strength. We mentioned differences between asymmetrical and symmetrical section around weak axis. The results caused by this differences have essential meaning on process of creating these models.

2:30 pm - 2:45 pm

Experimental and analytical study of Cold-Formed Steel (CFS) single-stud walls sheathed with FCB, CSB and MgO under compression

Sonkar, Chanchal[1]; Mittal, Achal K[1]; Bhattacharyya, Sriman K[2]; Kumar, Sachin[1]; Dewangan, Abhinav[3]

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Keywords: Cold-formed Steel, Buckling, Direct Strength Method, Compression, CUFSM

Cold-formed steel members are widely used in residential, industrial and commercial buildings as primary load bearing elements. It has been extensively used in lightweight framing of low and mid-rise residential constructions. Limited studies have been carried out on CFS wall panels sheathed with Fiber Cement Boards (FCB), Calcium Silicate boards (CSB), and Magnesium Oxide (MgO) Boards under compression. In the present study, CFS single-stud walls with FCB, Heavy Duty FCB (HDFCB), CSB, and MgO boards are experimentally tested under axial loading applied at a constant rate. Analytical modelling of CFS single-stud wall panels with the respective sheathing is carried out by calculating stiffness that the fastener-sheathing system supplies to the stud as bracing. Elastic buckling analysis of the stud with sheathing based springs is completed in CUFSM (Constrained and Unconstrained and Finite Strip Method) software version 4.05, consecutively axial load carrying capacity has been calculated using Direct Strength Method as per AISI S100 (Appendix 1). Analytical results seem to be in good agreement with the experimental results and the ratio between the two is varying from 0.84 to 1.06. There is significant amount of increment in the axial strength of CFS single-stud wall panels with the use of sheathing, which acts as a restraint. The maximum increase in axial strength is due to HDFCB boards, which is found to be 87% and 149% in one-sided and two-sided sheathed specimen respectively. The results obtained are interesting and useful for the research, academic and industrial community working in the area of CFS.

2:45 pm - 3:00 pm

Analytical Assessment of CFS Wall-Panels Sheathed with MgO Board

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Keywords: Cold-Formed Steel (CFS), Magnesium-Oxide Boards (MgO Board), CUFSM, Direct Strength Method (DSM).

Currently, Cold-formed steel (CFS) framed structures are being utilized at a large scale for residential as well as commercial purposes. CFS wall panels are conventionally sheathed using Gypsum boards (GB) and Oriented Strand boards (OSB). Use of MgO (Magnesium-Oxide) boards have also been started recently for sheathing. Few studies have been performed using MgO boards sheathing. This paper presents an analytical study on CFS wall-panel with MgO board sheathing and effect of parametric variation on strength of wall-panels'. The analytical study presented is done in 3 steps (1) Manually calculating the fastener-sheathing stiffness parameters (2) Calculating the load factors for the considered section through finite strip method (CUFSM tool: Constrained and Unconstrained Finite strip method) (3) Calculating nominal load (strength) by the Direct Strength Method (DSM) of AISI S-100 (Appendix 1) has been utilized. The aspect ratio of the wall-panels analyzed for this study is ranging from 1:1 to 1:2 with a frame height of 2400mm. In this study, it has been found that the strength of wall panel with stud spacing 600mm, screw spacing 150mm and aspect ratio of 1:1 is having 50% greater strength than bare frame wall panel of same specification. The paper also compares a strength variation of Wall-panel with MgO Board Sheathing with respect to CFS wall-panel with GB and OSB sheathing.

Structures 2: Bridges

Time: Friday, 13/Sep/2019: 1:45 pm - 3:00 pm · Location: C204
Session Chair: Pavel Ryjáček, Czech Technical University in Prague

1:45 pm - 2:00 pm

Influence of collision damage on load-carrying capacity of steel girder

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Kyushu Institute of Technology, Japan
Keywords: Steel Girder, Bridge, Collision Damage, Load-Carrying Capacity

An accident that a truck running underneath collides against an overpass bridge happens occasionally. The influence of the damage on the safety of the bridge must be judged right away. Yet it is not always an easy task, since the load-carrying capacity of a damaged girder has not been studied much. The first author has been involved in the evaluation of a steel girder overpass bridge damaged by collision. Based on the data obtained from this bridge, the load-carrying capacity of the deformed girder is investigated numerically in the present study. To be specific, the deformation of the main girder due to collision is reproduced by the finite element analysis and the deformed steel girder is loaded to evaluate the load-carrying capacity. The result indicates that as far as the damage is confined to the de-formation of the girder, the collision does not threaten the safety of the bridge even when the deformation is quite large.

2:00 pm - 2:15 pm

On the development of IoT platforms for the detection of damage in steel railway bridges

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Keywords: Assessment, SHM, damage detection, railway bridges

This paper presents the ongoing research related to the development of IoT platforms for the detection of damage in steel railway bridges. The development encompasses several fields from sensors, to damage detection, to data transmission, and to the infrastructure management system. The paper introduces the concept of regular availability of up-to-date data sets through an Internet-of-Things (IoT) approach that integrates information in cloud-based BIM platforms. Initial case studies have been developed in routinely per-formed load tests. Furthermore, laboratory experiences aimed at calibrating numerical methods under a controlled environment are being developed. Subsequently, complete systems encompassing different parts will be implemented in the form of real-case studies. The steps that have been performed so far include i) measurement of key characterizing data from these structures using different platforms ii) data transmission using different ranges and platforms iii) damage

detection using advanced FE-models and iv) understanding the data management platforms and the corresponding interoperability. The ongoing research project includes experiences in a joint effort between academia and industrial partners. The assessed structures include (but are not limited to) either new or existing steel railway bridges.

2:15 pm - 2:30 pm

Bracing Details for Trapezoidal Steel Box Girders

Armijos-Moya, S.V.; Wang, Y.; Helwig, Todd; Engelhardt, M.; Williamson, E.; Clayton, P.
University of Texas at Austin
Keywords: trapezoidal box girders, bracing, stability, steel, bridge

Trapezoidal steel box girders are often used for straight and horizontally curved bridges due to their high torsional stiffness and aesthetic appearance. However, during construction the girders consists of an open section that requires significant bracing. The bracing systems consists of a top lateral truss as well as internal and external cross frames or diaphragms. Decisions on the geometric layout of the girder can significantly impact the behavior of the bracing systems. This paper documents the results from an experimental and computational study on the behavior of steel tub girders with a variety of bracing systems. The experiments include elastic tests of the steel girder alone with a variety of bracing details as well as ultimate strength tests on composite girders. Efficient details are outlined as well as design expressions for the bracing and girder systems.

2:30 pm - 2:45 pm

Material Strength Statistics and Reliability Aspects for the Reassessment of End-of-Service-Life Steel Bridges

Kroyer, Robert; Taras, Andreas
Bundeswehr University Munich, Institute of Structural Engineering, Germany
Keywords: End-of-Service-Life Bridges, Material Strength Statistics, Reliability Analysis, Reassessment, Bayesian Statistics

The determination of the reliability of predictions of the load-carrying behaviour of engineering structures within a continuously ageing infrastructure is a topic of internationally increasing importance. Acknowledging this requirement, the proposed paper is devoted to the reassessment of existing steel bridge structures, particularly with regards to the ultimate limit state capacity of individual members and sections. For the appraisal of the material strength variability, a consistent and comprehensive collection of statistical material strength data for existing steel structures taken from the literature is presented. Beginning with puddle steel, the collected data of former steel products covers the era since about 1900 until today. In the proposed paper, the applicability of modern reliability assessment concepts in conformity with DIN EN 1990 to these steel products is investigated. This comprises an assessment of the proposed weighting factors within the application limits prescribed in the code. An estimation of the structural reliability's variability achieved by reassessment analyses following this concept is also comprised in this discussion. The proposed paper furthermore includes a probabilistic approach for the exploitation of material strength data available from material tests taken on any given site. Using Bayesian statistics, this approach is supposed to enable a more accurate reappraisal of the structural reliability of a specific in-service structure. A significant challenge of the presented concept for practical applications is given by the spatial variability of the strength parameters. Usually the material strength specimens are not taken directly from the section of interest. Therefore, the approach must also consider the degree to which the available specimens are representative for the investigated section. A provisional but feasible approach for adequate consideration of this issue is presented in the outlook.

2:45 pm - 3:00 pm

Thermorheological Testing and Modelling of Seismic Bearing Elastomers

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University of German Armed Forces Munich, Germany, Germany
Keywords: Seismic Elastomer Bearing, Dissipative Heating, Viscoelasticity, Prony Series, Finite Elemente Analysis

Seismic isolation systems protect civil infrastructure from collapse in the event of an earthquake. Usually the design is such, that the bridge structure is decoupled from soil to circumvent horizontal load transmission. In addition, the capability to dissipate energy is used, e.g. in elastomeric layers in bridge bearings. For the mentioned reasons, great experimental and modelling effort was spent over the past years to develop models to simulate the material's mechanical response to stresses and strains.

On the one hand, polymeric materials show a time dependent behavior, which for linear viscoelasticity can be described by a 'Prony-Series'. On the other hand, polymers are temperature dependent, characterized by at least two distinct temperature regions. In the energy elastic area, below the glass transition temperature ($T \ll T_g$), the glassy, brittle polymer reveals a relatively high stiffness, while in the entropy elastic area ($T \gg T_g$) it behaves rubber-like with significantly lower stiffness. This time-temperature correlation can be included through the 'Time-Temperature-Superposition-Principle' (TTSP) regarding thermorheologically simple materials. The aforementioned models to simulate the material response of the seismic elastomer bearings are mainly calibrated under isothermal conditions. However, during service time seismic, cyclic loading scenarios introduce dissipative self-heating inside the elastomeric layer and therefore require a calibration that considers temperature changes.

The focus of this contribution lies on the modelling and experimental investigation of the thermoviscoelastic behaviour of typical bridge bearing elastomers. The conduction of thermomechanical experiments such as 'Dynamic Mechanical Thermal Analysis' (DMTA) and 'Differential Scanning Caliometry' (DSC) allow a thermomechanical characterization. These experiments provide data to calibrate material parameters for a constitutive model. These obtained parameters are incorporated into state-of-the-art Finite-Element-Software to numerically investigate the experimental findings and assess the material's dissipative self-heating. In the outlook, the finding's importance as presented within this paper to an improved bridge design in seismic areas is highlighted.

Book of Abstracts of the International Colloquia on Stability and Ductility of Steel Structures

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