Wei-Wen Yu Center for Cold-Formed Steel Structures

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Abstracts of Conference Papers for Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures 2016

On November 9th and 10th, 2016 the Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures, the 23rd in the series of international specialty conferences, will be held in Baltimore, MD, USA. For further information regarding the conference, contact the Wei-Wen Yu Center for Cold-Formed Steel Structures (e-mail: ccfss@mst.edu , Telephone: 573-341-4471, Fax: 573-341-4476,), or visit the Center's website at http://ccfssonline.org for a PDF copy of the brochure and program as well as online registration. This Technical Bulletin provides a brief summary of the papers that are scheduled to be presented and will appear in the conference proceedings.

Characterization of Cold-Formed Steel Framed Diaphragm Response Under In-Plane Loading and Influence of Non-Structural Gypsum Panels, Patrick Latreille, Violetta Nikolaidou, Colin A. Rogers, Dimitrios G. Lignos

The in-plane response of CFS framed diaphragm structures subjected to seismic excitation is not well understood. At present, the North American AISI S400 Standard does not include a seismic design procedure for CFS framed diaphragms for use in Canada, and offers limited information for their use in the US. In addition, the effect of non-structural components on the lateral strength and stiffness of the diaphragm component has yet to be explored. In an effort to provide insight into the complex nature of the diaphragm structure and the influence of non- structural components an experimental program was initiated in the Jamieson Structures Laboratory at McGill University focusing on the characterization of the behaviour of CFS framed - wood sheathed diaphragms under in-plane loading. This paper presents the results for four diaphragm configurations with oriented strand board sheathing (OSB) tested under monotonic and reversed cyclic loading following the cantilever test method. The 3.7m x 6.1m diaphragm specimens were constructed with different structural configurations as well as non-structural gypsum panels below the steel framing. Design predictions for the shear strength and deflection of the diaphragm specimens were obtained using the information available in the AISI S400 Standard.

Finite Element Modeling of Concrete Shrinkage in Composite Deck Slabs, Vitaliy V. Degtyarev

This paper presents finite element models of composite deck slabs subjected to restrained concrete shrinkage. The models created in ANSYS and validated against test data were based on the assumption of the full shear interaction between the deck and the concrete and accounted for concrete creep, cracking, and nonlinear stress-strain relationship. Concrete shrinkage was modeled by temperature changes applied to concrete. The effects of different shrinkage profiles, concrete creep, and deck slab properties on the long-term concrete and deck strains are resented. Future research work is outlined.

Numerical Simulations of Solid and Slotted Cold-Formed Steel Channels with Different Boundary Conditions in Shear, Vitaliy V. Degtyarev and Natalia V. Degtyareva

This paper presents results of a numerical study on the shear strength of cold-formed steel channels with solid and slotted webs. The effects of four different boundary conditions—test setup, realistic, and simply supported with free and restrained ends—on the elastic shear buckling load and the ultimate shear strength were considered. The study was performed on finite element models developed in ANSYS and validated against test data. The obtained results showed that the elastic shear buckling loads and the ultimate shear strengths of the slotted channels are more sensitive to the boundary conditions when compared with the solid channels. The simply supported boundary conditions can reasonably well simulate the test setup boundary conditions of the solid channels but not the slotted channels. The realistic boundary conditions cannot be accurately simulated by the simply supported boundary conditions for the solid and slotted channels.

Resistance of Arc Spot Welds- Update to Provisions, B. Paige Blackburn and Thomas Sputo

The AISI S100-12 provisions for arc spot welds have not be reviewed since 1999. This study performs a comprehensive analysis of the entire arc spot weld data base including data from four new research studies and reconsiders AISI S100-12 resistance equations with data from 450 specimens. Most AISI S100-12 equations were found to be conservative, particularly for sheet tearing failure modes. However, the equation for arc spot weld fracture under tensile load was found to poorly predict the data base test results. AISI S100-12 provision improvements are recommended not only for the resistance equations and factors, but also for the effective weld diameter calculation, maximum sheet thickness limitation, and design approaches for various sheet configurations.

Application of the Direct Strength Method to Steel Deck, Randall Keith Dudenbostel and Thomas Sputo

With the reorganization of the AISI S100 Standard, the Direct Strength Method (DSM) takes a position of equal footing with the Equivalent Width Method (EWM) for calculating the strength of cold-formed steel cross sections. The majority of previous DSM studies focused on C and Z profiles, while little study of panel sections, especially steel deck sections, has been performed. A study was undertaken to determine and compare the behavior and usable strength of existing floor and roof deck sections with both DSM and EWM. The Cornell University – Finite Strip Method (CUFSM) software was used for the elastic buckling analysis, taking into account the wide, continuous nature of installed deck sections. Flexural capacity was analyzed for positive and negative flexure to account for gravity loading as well as uplift of the steel deck sections.

Graphical representations of the relationships for DSM strength to the EWM strength ratio vs. material width to thickness ratio were developed and are illustrative as to the trends seen. DSM predicts lower flexural strength versus EWM for sections with relatively wide and thin compression flanges (larger b/t ratios).

New SDI Diaphragm Design Manual, Larry Luttrell, John Mattingly, Walter Schultz, Thomas Sputo

The Steel Deck Institute (SDI) has released the new and long awaited 4th Edition of the Diaphragm Design Manual (DDM04). This new edition complies with the requirements of the ANSI/AISI S310-13 North American Standard for the Design of Profiled Steel Diaphragm Panels. At 408 pages, the 4th Edition is larger than its predecessor and will be an invaluable resource to structural designers because of the background information, design examples, and
extensive load tables.

Experiments on column base stiffness of long-span cold-formed steel portal frames composed of double channels, H.B. Blum and K.J.R. Rasmussen

Cold-formed steel haunched portal frames are popular structures in industrial and housing applications. They are mostly used as sheds, garages, and shelters, and are common in rural areas. Cold-formed steel portal frames with spans of up to 30m (100 ft) are now being constructed in Australia. As these large structures are fairly new to the market, there is limited data on their feasibility and design recommendations. An experimental program was carried out on a series of portal frame systems composed of back-to-back channels for the columns, rafters, and knee braces. The system consisted of three frames connected in parallel with purlins to simulate a free standing structure, with an approximate span of 14 m (46 ft), column height of 5.3 m (17 ft), and apex height of 7 m (23 ft). Several configurations were tested including variations in the knee connection, sleeve stiffeners in the columns and rafters, and loading of either vertical or combined horizontal and vertical loads. Deflections were recorded at various locations to measure global and local movements of the structural members, as well as column base reactions and base rotations. It was determined that the column bases are semi-rigid and further column base connection tests were completed to quantify column base connection stiffness for bending about the column major and minor axes, as well as twist. Results of the column base connection stiffness are presented as well as the implications for frame design.

Seismic performance investigation of cold-formed steel framed shear walls with steel sheathing, Feng Ruo-qiang, Xu Peng-hui

Cold-formed steel (CFS) framed shear walls with steel sheet sheathing can achieve higher shear resistance compared to conventional CFS framed shear walls. Experimental and numerical investigation of seismic behavior was present on two CFS shear walls sheathed with steel sheet for the base layer combined with gypsum wallboards for the face layer on both sides. Monotonic shear and cyclic loading tests were conducted on wall specimens. The failure mechanism, bearing capacity, stiffness and ductility of specimens were obtained. On the basis of rational simplification of CFS framed shear walls, the finite element software ABAQUS was used to simulate the monotonic behavior of CFS shear walls and the structural analysis software OpenSees was used in developing and calibrating 2D models of reversed cyclic shear wall test. A comparison between the numerical simulations and the test results showed a good agreement between the results of the numerical studies and the test results. The conclusions of this study can be applied to the seismic design of CFS framed shear walls.

Unconstrained cross-sectional shape optimisation of cold-formed steel beams and beam-columns, Bin Wang, Benoit P. Gilbert, Guillaume L. Bosco, Hong Guan and Lip H. Teh

This paper is focused on optimising the cross-sectional shapes of simply supported, singly-symmetric and open-section cold-formed steel (CFS) beams and beam-columns without manufacturing or assembly constraints. A previously developed Genetic Algorithm (GA) is used in this study. Fully restrained and unrestrained beams against lateral deflection and twist, as well as unrestrained beam-columns are optimised, of which the nominal member capacities are determined by the Direct Strength Method (DSM). The optimised cross-sectional shapes are presented and the evolution of the unrestrained cross-sectional shapes for various combinations of axial load and bending moment is analysed and discussed.

Buckling Behaviour of Cold-Formed Steel Beams under Bending and Torsion, Hong-Xia Wan and Mahen Mahendran

This research is concerned with the buckling behaviour and design of cold-formed steel beams subject to combined bending and torsional actions. A finite element model considering the effects of initial geometrical imperfections and residual stresses was developed to simulate the combined bending and torsion of cold-formed steel beams. The finite element model was used to conduct analysis on cold-formed lipped channel sections, Z sections and hollow flange channel sections. Elastic buckling analysis was first conducted to study their buckling modes and buckling loads. Nonlinear analysis including the effects of large deformation and material yielding was conducted to obtain their ultimate buckling strength. The interaction between the ultimate bending and torsional moment capacities was studied and appropriate design rules were suggested. This paper presents the essential details of this research and the important results.

Buckling strength of cold-formed circular steel column subjected to axial load, Ayana ITO, Nobutaka SHIMIZU, Keiichi SATO and Yoshimichi KAWAI

In this study, the global buckling behavior of a cold-formed circular steel column was discussed with a focus on the effects of its mechanical properties and initial imperfections on the behavior. As the first step, the stress–strain curves of the column under tensile and compressive loads as well as its residual stresses were investigated. Subsequently, a finite element analysis was conducted to clarify if the analysis properly simulated the stub column behavior. The analysis results obtained using measured compressive stress–strain curves and residual stresses agreed well with experimental results. Finally, another finite element analysis was performed on the long column buckling to examine the effects of its mechanical properties and initial imperfections. It was shown that the global buckling strength was affected not only by imperfections such as residual stress and out-of-straightness but also by the anisotropic mechanical properties of the material.

Finite element investigations of the effect of residual stress in cold-formed sigma beams, Feiliang Wang, Jian Yang

Press braking is a cold forming operation used to fold the angle along the flat sheet between the top punch and bottom die. The residual stress will be induced in this process as a result of plastic deformation. In the welding process, a dynamic thermal cycle is introduced to generate a non-uniformly temperature distribution on the heat affected zone (HAZ), and the residual stress also occurs in the process as a result of uneven cooling along the welding bead. The existence of residual stress can superimpose onto the external loadings to affect the stiffness and load resistance capacity of the structures. Therefore, a comprehensive understanding of the distribution and the impact of residual stress on the performance of cold-formed sections (CFS) is essential.

Shear Resistance of Cold-Formed Steel Framing Wall with X Strap Bracing, Chi-Ling Pan, Chang-Chan Huang, and Meng-Hsiu Tsao

This research is concentrated on the study of structural strength and behavior of cold-formed steel frame with strap bracing subjected to horizontal loads. The wall specimens with and without calcium silicate board sheathing were tested to compare the differences of shear resistance. Based on the test data, the ultimate strength, stiffness, ductility ratio, and failure behavior were studied for each specimen, and the wall's movements were also discussed in this paper. The cold-formed steel framing wall without bracing from previous study was introduced for the comparison purpose. As expected, the ultimate strength was increased for the cold-formed steel wall sheathed with calcium silicate board after installing strap bracing. However, the initial stiffness and ductility ratio of cladded wall specimens with bracing did not show much difference as compared to cladded wall specimens without bracing. It was found that the ultimate strength of cold-formed steel wall frame installed with both sheathing and strap bracing is not the sum of ultimate strengths of cold-formed steel wall frame with sheathing and cold-formed steel wall frame with strap bracing only. A better performance of energy absorption beyond the portion of ultimate strength was found for the wall specimen with both sheathing and bracing. It was also observed that the failure type and location are different for the cladded wall specimens with and without bracing.

Sheathing Overlapping and Attachment Methods for Cold-Formed Steel Shear Walls with Corrugated Steel Sheathing, Mahsa Mahdavian, Wenying Zhang, Cheng Yu

Cold-formed steel (CFS) shear walls sheathed with corrugated steel sheathing are a feasible solution to non-combustible high structural performance CFS shear walls in mid-rise buildings. Corrugated steel sheathings have high in-plane strength and stiffness due to the cross sectional shape of the sheet. This paper presents an experimental study on two specific issues: (1) the sheathing overlapping configurations and their impact to the shear wall performance, (2) the attachment method for sheathing to framing. For the overlapping issue, one overlap and two overlaps in the corrugated sheets were experimentally investigated, it was found that the overlap

differences did not cause significant different behaviors and strength of CFS shear walls. For the sheathing-to-framing attachment method, self-drilling screws and dual spot welding were studied. A portable spot welder with dual heads was used in this research. Connection tests and full scale shear wall tests were conducted to study the two different connection methods. It was found that the dual spot welding yielded a weaker connection than the conventional self-drilling screw connections. This paper presents the details of the test programs, research findings and recommendations for CFS shear wall applications.

Simulating the Seismic Performance of Cold-Formed Steel Framed Buildings using Corrugated Sheet Shear Walls, Wenying Zhang, Mahsa Mahdavian, Yuanqi Li, Cheng Yu

Cold-formed steel framed shear wall sheathed with corrugated steel sheets is a promising shear wall system for low- and mid-rise constructions at high wind and seismic zones due to its advantages of non-combustibility, high shear strength, and high shear stiffness. A lot of work has been done on this subject. However, all the previous work is focused on the wall panel levels and more research work is needed on the entire building systems. The objective of this paper is to investigate the response of a cold-formed steel framed building with corrugated sheet sheathing subjected to earthquake excitation primarily through nonlinear time history analysis employing the incremental dynamic analysis (IDA) framework. High fidelity models were simulated in OpenSees program. The detailed modeling information and system assessment are presented in this paper.

Incorporation of Elastic Local Buckling in a Plain Channel Section Beam Subjected to Double-curvature Bending: An Effective-width Approach, Edwin Lim, Barry J. Goodno, James I. Craig

When electrical cabinets are subjected to lateral loads, such as earthquakes, the beams of the cabinet frame typically experience double-curvature bending deformation. These beams are usually constructed from cold-formed plain channel sections so they are vulnerable to elastic local buckling near their ends, where high stresses from applied loads are more likely to develop. To capture local buckling behavior, structural engineers typically use high-fidelity finite element models, but this approach can be complex and computationally expensive. A Timoshenko beam element model is simpler and less computationally costly but it is not capable of capturing local buckling behavior. In this paper, a hybrid Timoshenko beam element model augmented withnonlinear nodal springs is proposed to capture elastic local buckling. Local buckling behavior is computed using cross sectional moment-curvature data generated by an effective-width equation, and the results of computations are validated using a high fidelity finite element model (referred to as the benchmark model) of the beam. The resulting reduced rotational stiffness is incorporated in nonlinear elastic rotational nodal springs introduced at the beam ends. A comparison of the hybrid and benchmark model results is presented to confirm the accuracy of the hybrid model.

Development of a Method to Generate a Simplified Finite Element Model for an Electrical Switchboard Cabinet, Edwin Lim, Barry J. Goodno, James I. Craig

Electrical switchboards are one of the key pieces of equipment used in operations of most critical facilities such as hospitals and emergency services buildings. Unfortunately, past observations have shown that the switchboard cabinet and its contents may be vulnerable to damage or failure during an earthquake. An electrical switchboard cabinet is a complex structure typically constructed using cold-formed steel frame members enclosed by steel panels and containing a variety of switchgear and bus bars. The panels are usually fastened to the steel members by screws, and the steel members are connected together by bolts or screws. The structural behavior of the cabinet can be evaluated using shake table testing and/or high fidelity finite element models. However, these methods are relatively expensive, highly specific, and interpretation of the results may be difficult. Therefore, a method to formulate a simplified finite element model for the cabinet is proposed in this study. The simplified model consists of beam elements (Timoshenko), shell elements and springs. This model can be constructed and executed computationally at a lower cost, and interpretation of the results is a simpler assignment. The present model has the capability to capture the effect of warping deformation in the frame members and possible nonlinear behaviors of the cabinet, such as: local buckling at the end of frame members due to high bending moments, failure of the screw connections and buckling of the panels. The simplified model is validated using a high fidelity model of the cabinet under 1st-order and 2nd-order pushover analyses. Future work to incorporate structural models for the internal components is also discussed.

On the Direct Strength Design of Cold-Formed Steel Columns Failing in Local-Distortional Interactive Modes, André Dias Martins, Dinar Camotim and Pedro Borges Dinis

This paper present and discusses proposals for the codification of efficient design approaches for cold-formed steel columns affected by local-distortional (L-D) interaction. These proposals, based on the Direct Strength Method (DSM), were developed, calibrated and validated on the basis of experimental and numerical (shell finite element) failure load data concerning columns with several cross-section shapes and obtained from investigations carried out by various researchers. Three types of L-D interaction are taken into account, namely “true L-D interaction”, “secondary local bifurcation L-D interaction” and “secondary distortional bifurcation L-D interaction”. Moreover, previously available DSM-based design approaches to handle column L-D interactive failures are reviewed and their merits are assessed and compared with those exhibited by the present proposals. The paper also presents reliability assessments of the failure load predictions provided by the available and proposed DSM-based design approaches, following the procedure prescribed by the current version of the North American Specification (NAS) for the Design of Cold-Formed Steel Structures (AISI 2012).

Tilt Bearing Capacity of Single-Shear Bolted Connections without Washers. Mehmet E. Uz and Lip H. Teh

This paper examines the accuracy of design equations specified in the North American and European codes for cold-formed steel structures in determining the ultimate tilt bearing capacity of single-shear single-row bolted connections without washers in flat steel sheets. It points out that the code equations do not properly distinguish the tilt bearing failure mode from the conventional bearing failure mode, which is typical of double-shear connections and single-shear connections with washers. The tilt bearing capacity is affected by the width of the connected sheet, and its capacity does not vary linearly with either the sheet thickness or the bolt diameter. Based on the test results of 150 specimens composed of G2 and G450 sheet steels having various dimensional configurations, this paper proposes a design equation that is dimensionally consistent and that is considerably more accurate than all the code equations. The proposed equation was also verified against single-shear single-row bolted connections tested by independent researchers which failed in the tilt bearing mode. A resistance factor of 0.75 is recommended for use with the proposed equation for determining the ultimate tilt bearing capacity of single shear single-row bolted connections in cold-reduced steel sheets.

Block Shear Equation and Rupture Resistance Factor for Cold-Formed Steel Bolted Connections, Lip H. Teh and Mehmet E. Uz

This paper proposes the most accurate equation for determining the block shear capacity of a bolted connection in a tension brace composed of material that satisfies all the ductility requirements of the North American cold-formed steel structures specification. The block shear test results of SS400 steel specimens obtained by independent researchers and those of G450 sheet steel specimens loaded by the authors in the rolling direction are used to evaluate the proposed equation. This paper also discusses the resistance factor to be universally applied to all bolted connections failing in rupture. A reliability analysis of the current shear-out design equation is carried out for this purpose. A uniform resistance factor of 0.75 is recommended for the design equations against block shear rupture, shear-out rupture, and tensile rupture in a flat sheet, in a channel brace bolted at the web, in an angle brace bolted at one leg, and in a staggered bolted connection, which are contained in the “Rupture” section of the North American Specification for the Design of Cold-formed Steel Structural Members.

First-order Generalized Beam Theory for Curved Members with Circular Axis, Nuno Peres, Rodrigo Gonçalves and Dinar Camotim

This paper presents a first-order Generalized Beam Theory (GBT) formulation for thin-walled members with circular axis and undergoing complex global-distortional-local deformation. The fundamental equations are derived on the basis of the usual GBT kinematic assumptions (Kirchhoff, Vlasov and wall in-plane inextensibility), leading to a formulation able to retrieve accurate solutions with only a few cross-section deformation modes (cross-section DOFs). It is shown that the classic Winkler and Vlasov theories can be recovered from the derived formulation. A GBT-based finite element is use to analyze numerical examples illustrating the application and potential of the proposed formulation.

Proposal for the Codification of a DSM Design Approach for Cold-Formed Steel Short-to-Intermediate Angle Columns, Pedro Borges Dinis and Dinar Camotim

This paper presents a proposal for the codification of an efficient design approach for cold-formed steel short-to-intermediate equal-leg angle columns, consisting of a slight modification of a design approach developed by Dinis & Camotim (2015) and based on the Direct Strength Method (DSM). After (i) collecting the available experimental and numerical failure load data, comprising fixed-ended and pin-ended columns with several geometries (cross-section dimensions and length) and reported by various researchers, and (ii) briefly reviewing the mechanical reasoning behind the proposed procedures, the search for new/simpler expressions to provide the DSM design curves is addressed. Their merits are assessed through (i) the quality of the estimates of the available failure load data and (ii) the determination of the corresponding LRFD resistance factors. Concerning the latter, it is shown that the value recommended, for compression members, by the North American Specification (NAS) for the Design of Cold-Formed Steel Structural Members (AISI 2012), namely fc=0.85, can also be adopted for angle columns.

Experimental tests for the seismic response evaluation of cold-formed steel shear walls sheathed with nailed gypsum-based panels, Luigi Fiorino, Vincenzo Macillo, Maria Teresa Terracciano, Tatiana Pali, Bianca Bucciero, Raffaele Landolfo

The European project named "Energy Efficient LIghtweight-Sustainable-SAfe-Steel Construction" (Project acronym: ELISSA) is devoted to the development and demonstration of cold-formed steel (CFS) modular systems. In particular, these systems are nano-enhanced prefabricated lightweight steel skeleton/dry wall construction with improved thermal, vibration/seismic and fire performance, resulting from the inherent thermal, damping and fire spread prevention properties. The different building performances are studied and improved by means of experimental and numerical activities organized on three scale levels: micro-scale, meso-scale and macro-scale. In particular, the evaluation of the seismic performance is carried out at the University of Naples by means tests on connections (micro), seismic-resistant systems (meso) and full-scale two stories house prototype (macro). From a structural point of view, the system is a sheathed-braced CFS solution, in which the seismic resistant elements are made of CFS stud shear walls laterally braced by gypsum-based panels. In the adopted solution, the sheathing panels are attached to the CFS frame by means of ballistic nails, whereas clinching points are used for steel-to-steel connections. The present paper illustrates the results of meso-scale tests performed on

four full scale shear walls, in which the influence of the aspect ratio, the type of loading and the effect of finishing was investigated.

Experimental investigation into steel storage rack beam-to-upright bolted connections, Liusi Dai, Xianzhong Zhao and Chong Ren

For unbraced steel storage racks, the down-aisle stability depends largely on the performance of beam-to-upright connections and column bases. Boltless connections are generally used in order to make rack structures easy to assemble and feasible to adjust the storey height. Recently, storage racks are designed to carry large amounts of goods and they are therefore raise a considerable height, which makes the improvement of the structural stability to be sufficiently important. Under the circumstances, tab-connected beam-to-upright connections with bolts are gradually used in steel storage racks. Compared with boltless connections, the stiffness, strength and ductility of the bolted connections are improved to some extent. This paper presents an experimental investigation into the moment-rotation characteristic of steel storage rack beam-to-upright bolted connections under monotonic loads. Seven groups of specimens were tested with different constructional details and three identical specimens were repeated for each group. Moreover, the single cantilever test method was employed to study the rotational behaviour of connections. Effects of various parameters, such as upright thickness, beam height and tab numbers on connection behaviour are discussed and presented in this paper. The experiments show that the failure modes of bolted beam-to-upright connections depend on the relative thickness between the upright and beam-end-connector, as well as the relative height between the beam and beam-end-connector. Furthermore, the results obtained from the present study highlight that the behaviour of connections, such as stiffness and ultimate moment capacity, are considerably influenced by the specific constructional details.

Effect of Web Perforation on the Behaviour of Cold-formed Steel C-shape Slender Column Subjected to Non-uniform Cross-sectional Distribution of Elevated Temperature, S. Yang and L. Xu

Presented in this paper is a numerical investigation on the effect of web perforations on the behaviour of cold-formed steel C-shape columns subjected to non-uniform cross-sectional distribution of elevated temperature with use of finite element analysis. The length of web perforation investigated varies from 0 mm to 630 mm (25 in.). The non-uniform cross-sectional distributions of elevated temperatures are obtained from finite element thermal analysis of insulated CFS walls subjected to standard fire up to 105 minutes. Sequentially coupled thermal-stress analyses were carried out under a transient state condition. The concentrically loaded cold-formed steel C-shape columns with load ratios of 0.6, 0.7, 0.8 and 0.9 are investigated. Initial global geometrical imperfection is accounted for in the. It is found that the column failed by global buckling about its weak axis together with the local failure around the region of the web perforation at mid-height of the column and thermal bowing towards the fire-exposed side. The obtained results from the finite element analysis demonstrate that the web perforation has an influence on the temperature distribution of the cross-section of the C-shape column, but the temperature gradient within a cross-section is hardly associated with length of the web perforation. As a result, the differences of failure times among the cold-formed steel C-shape columns with different lengths of web perforation subjected to a same load ratio are found to be within 10%.

An Improved Two-stage Seismic Analysis Procedure for Mid-Rise Buildings with Vertical Combination of Cold-Formed Steel and Concrete Framing, X. Yuan and L. Xu

Presented in this paper is an improved two-stage analysis procedure for evaluating the seismic load of the mid-rise buildings with vertical combination of cold-formed steel and concrete framing. By comparing the improved procedure to the one prescribed in ASCE 7, it is found the stiffness requirement of the two-stage analysis procedure stated in ASCE 7 may be overrelaxed, which may consequently result in the underestimation of the base shear of the upper structure in certain cases. Furthermore, the lateral load at the top storey of the upper structure evaluated by ASCE 7 two-stage analysis procedure may also be considerably underestimated. Therefore, an additional amount of lateral load is proposed to be applied to the top of the upper structure. The results of the improve and the existing ASCE 7 two-stage analysis procedures are compared to those of the elastic modal response spectrum analysis, respectively. Comparing to the one prescribed in ASCE 7, the proposed improved two-stage analysis procedure yields more accurate results.

Behavior of Cold-Formed Steel Semi Rigid Connections, Ruby Freya, R. Senthil, W.Jeoffray Merin, R. Savavanakumar, Kuber, M.Gowtham

Ductility and inelastic performance are important considerations in aseismic design of buildings. The dissipation of energy due to inelastic deformation is predominantly required in the connections like beam column joints. It is necessary to design these joints as semi-rigid for its economic and structural benefits. Semi-rigid connections have highly nonlinear behaviour that makes the analysis and design of frames difficult and complicated. Steel structures are highly regarded for their seismic performance. It is required to understand and study the inelastic behavior of steel connections which would help in an economical and simpler design. This paper involves the modeling of deformational behaviour of a cold formed steel connection in a finite element software simulating the real time behavior. The ultimate moment and rotation is studied for different semi rigid connections after validation of the model.

A Finite Element Method for Distortional Buckling Analysis of Thin-Walled Members, Sheng Jin, Xiao Jiana, Rui Cheng, Shidong Niea, Mingyue Cheng

This paper presents a method for distortional buckling analysis of thin-walled members without assuming longitudinal shape of buckling modes. In this method, the pure distortional elastic buckling loads and deformation modes are achieved by performing a linear buckling analysis of a specially constrained finite element model of the thin-walled member in ANSYS. The constraints on each cross-section are applied independently and can be divided into two parts. The first part, by which distortional buckling can be distinguished from local buckling, depicts the transvers deformation of a cross-section, while the second part originated from longitudinal displacement patterns of distortional modes is used to distinguish this type of buckling from global buckling. Transverse membrane extensions are permitted in the proposed distortional buckling mode. A numerical example is given to demonstrate the method.

Identifying shear buckling coefficients for channels with rectangular web stiffeners using the generalised cFSM, Morgan A. Rendall, Gregory J. Hancock and Kim J.R. Rasmussen

The Direct Strength Method (DSM) of design for cold-formed sections was recently extended in the North American Specification for Cold-Formed Steel Structural Members (NAS S100:2012) to include members in shear. The method has largely been developed on the basis of work done on lipped channel sections. To utilise the method requires the critical shear buckling load of the section, which may be determined from a minimum point on the signature curve for the section in pure shear. However when longitudinal web stiffeners are added to the channel a minimum may not exist, or may occur at half-wavelengths where the critical buckling mode is localised in the individual vertical portions of the web rather than involving the full web as an essentially continuous element, as occurs for a plain lipped channel in local shear buckling. This paper explores the application of the recently-developed generalised constrained finite strip method (cFSM) to determine critical shear buckling loads for lipped channels with rectangular web stiffeners, from which shear buckling coefficients may be back-calculated. The addition of the stiffener leads to new distortional modes, deemed web-distortional modes, that play an important role in the buckling behaviour of web-stiffened channels at half-wavelengths where buckling involves deformations of the web as a continuous element. Using the cFSM, combinations of pure local modes and the web-distortional modes are considered to produce modal solutions. These modal solutions always give a minimum regardless of section and these minima are used to identify critical buckling half-wavelengths. The critical shear buckling loads are then taken as those at the same half-wavelengths on the corresponding traditional FSM signature curves for the sections. The proposed method is appropriate for sections with small stiffeners, as are used in practice.

The design and development of new cold roll formed products by finite element modelling and optimisation, V.B. Nguyen, P.K.C. Wood, M.A. English and M.A. Castellucci

The design and development of new cold roll formed products can incur significant cost and the product may not be optimised for either performance or manufacture. This paper describes a new method to develop an optimum structural design of profile by cold roll forming using a combined approach of finite element analysis and optimisation techniques. To illustrate the concept, the design and development of a new channel beam and a new drain grating subjected to bending are presented. The two case studies, demonstrate how a roll formed profile may be optimised to improved structural performance through use of stiffeners and/or dimples. Improved performance of cold roll formed products is achieved by increasing the strength of the product without increasing the amount of the material used. The results of this paper clearly demonstrate an efficient and effective method and tool set to optimise design for performance and manufacture of cold roll formed products.

Design of new cold rolled purlins by experimental testing and Direct Strength Method, V.B. Nguyen, B. Cartwright and M.A. English

New cold roll formed channel and zed sections for purlins, namely UltraBEAMTM2 and UltraZEDTM2, have been developed by Hadley Industries plc using a combined approach of experimental testing, finite element modelling and optimisation techniques. The new sections have improved strength to weight ratio by increasing the section's strength by using stiffeners in the section webs. The European standards, Eurocode 3, use a traditional Effective Width Method to determine the strength of a cold formed steel member. However, the design of the new sections UltraBEAMTM2 and UltraZEDTM2 using this method is very complicated in calculating the effective section properties as these sections contain complex folded-in stiffeners. In addition, the incorporation of competing buckling modes such as distortional buckling can be difficult to analyse. To overcome difficulties of using Eurocode 3 or such a standard with the Effective Width Method for the design of these sections, the Direct Strength Method (DSM) is adopted for determining the section strengths. Four-point beam bending tests were carried out to determine the buckling and ultimate bending capacity of the UltraBEAMTM2 and UltraZEDTM2 sections. Results of experimental testing and Finite Element Analysis were initially used as validation for the design using the DSM. The DSM results in terms of in bending moment capacities were then compared with the experimental test results for a broader data in which the UltraBEAMTM2 and UltraZEDTM2 sections had a range of different width-to-thickness ratios. It showed an excellent agreement between test and DSM design values. It is concluded that the DSM is a powerful tool for the design and optimisation of the new cold roll
formed channel and zed purlins.

Tests of Cold-Formed Ferritic Stainless Steel Beams, Lianghao Li, Ben Young

Ferritic stainless steel is characterized by its low or even no nickel content, which provides a good alternative to a more commonly used austenitic stainless steel (with 8.0-10.0% nickel content) in structural application. The low nickel content attributes to low initial

material cost and more stable price for ferritic stainless steel. A series of four-point bending tests was conducted on both square and rectangular hollow sections to investigate the flexural performance of cold-formed ferritic stainless steel hollow sections. The experimental results obtained from this test program and the available data in the literature on cold-formed ferritic stainless steel beams were used to assess the current design rules in the American Specification and direct strength method. It is shown that the current design specifications provide conservative predictions for the cold-formed ferritic stainless steel beams.

Shear behavior of screw connection between cold formed steel and gypsum sheathing at elevated temperature, Wei Chen, Jihong Ye

The screw connections between cold-formed steel (CFS) and gypsum sheathing play an important role in the axial and lateral performance of CFS wall panels. Previous researches were mainly focus on the shear behavior of such screw connections at room temperature. This paper carried out a preliminary experimental investigation on the mechanical performance of screw connections with single layer gypsum sheathing at elevated temperatures. Limited to the cavity dimension of the furnace, the single-lap test of CFS coupon - fastener-sheathing connection was adopted and compared with the previous test results of sheathing-to-profile screw connections at room temperature. The failure of screw connections with single layer gypsum sheathing was identified as the breaking of the sheathing edge at elevated temperatures and a sharp decrease of the shear strength was observed beyond 150 °C. In addition, the load-displacement curves of screw connections were well predicted by an exponential model with the post-peak branch at elevated temperatures.

Experimental Investigation of Cold-Formed C-Sections with Central Square Holes in Shear, Cao Hung Pham, Andreas Pelosi, Thomas Earls and Gregory J. Hancock

The North American Specification S100:2012 Edition has recently included DSM design rules for unperforated channel sections in shear. However, there are no rules presented in this standard for the DSM in shear for sections with holes. Recently, a testing program has been performed at the University of Sydney to determine the ultimate strength of high strength cold-formed C-sections with a thickness of 1.5 mm and central square holes of varying sizes. Three different sizes of the square holes were chosen for testing. For thin sections, the DSM shear curve was found to be applicable for design of sections with square holes up to certain sizes. For larger hole sizes, the DSM shear curve without tension field action (TFA) should be utilised as the channels with large reduced web area do not mobilise the TFA. This paper presents a further experimental investigation on the same cold-formed C-sections but thicker thicknesses of 1.9 mm and 2.4 mm. The square holes were also cut centrally with three different hole sizes. As the sections are thicker, the yield criterion plays a more important role. The proposals for different shear yield load are made in DSM equations for shear. Recommendations for an extension to the DSM in shear for channel sections with square holes are given in the paper.

A Direct Strength Method (DSM) of Design for Channel Sections in Shear with Square and Circular Web Holes, Song Hong Pham, Cao Hung Pham and Gregory J Hancock

The Direct Strength Method (DSM) design rules for cold-formed steel members in shear have been incorporated recently into the North American Specification (AISI S100-12) and are being implemented in the Australian standard (AS/NZS 4600:2005). The method, which was calibrated for unperforated members only, requires two inputs including the buckling load Vcr and the shear yielding load Vy. For members with square web cut-outs, Vcr can be computed by either the Spline Finite Strip Method (SFSM) or the tabulated values based on the shear buckling coefficients kv as studied by CH Pham or the Finite Element Method (FEM). However, Vy has not been accurately formulated including holes. This paper represents a practical model to obtain Vy for members with central openings subjected to predominantly shear. The model ranges from very small holes where traditional shear yielding predominates to large holes where Vierendeel action dominates. The model is verified with the DSM design formulae using the predominantly shear tests recently conducted at the University of Sydney and Queensland University of Technology with both square and circular web openings and for shear spans with aspect ratios of 1.0.

Analyses of thin-walled sections under localised loading for general end boundary conditions – Part 1: Pre-buckling, Van Vinh Nguyen, Gregory J Hancock and Cao Hung Pham

The Semi-Analytical Finite Strip Method (SAFSM) for pre-buckling analysis of thin-walled sections under localised loading has been developed for general end boundary conditions. For different boundary conditions at supports and loading point, different displacement functions are required for both flexural and membrane displacements. As the stresses are not uniform along the member due to localised loading, the pre-buckling analysis also requires multiple series terms with orthogonal functions. This paper briefly summaries the displacement functions used for different boundary conditions. In addition, the theory of the SAFSM for pre-buckling analysis of thin-walled sections under localised loading with general end boundary conditions is developed. The analysis is benchmarked against the Finite Element Method (FEM) using software package ABAQUS/Standard. The results from this pre-buckling analysis are deflections (pre-buckling modes) and membrane stresses which are used for the buckling analysis described in Part 2 - Buckling in the companion paper.

Analyses of thin-walled sections under localised loading for general end boundary conditions – Part 2: Buckling, Van Vinh Nguyen, Gregory J Hancock and Cao Hung Pham

Thin-walled sections under localised loading may lead to buckling of the sections. This paper briefly introduces the development of the Semi-Analytical Finite Strip Method (SAFSM) for buckling analyses of thin-walled sections under localised loading for general end boundary conditions. This method is benchmarked against the Finite Element Method (FEM). For different support and loading conditions, different functions are required for flexural and membrane displacements. In Part 1- Pre-buckling described in a companion paper at this conference, the analysis provides the computation of the stresses for use in the buckling analyses in this paper. Numerical examples of buckling analyses of thin-walled sections under localised loading with different end boundary conditions are also given in the paper in comparison with the FEM.

Recent Developments in the Australian/New Zealand Standard AS/NZS 4600 for Cold-Formed Steel Structures, Gregory J Hancock

The Australian/New Zealand Standard AS/NZS 4600 is currently under revision based in part on the latest edition of the North American Specification AISI S100:2012 and partly based on the latest research in Australia and New Zealand. The Direct Strength Method (DSM) of design has undergone substantial research since the 2005 edition of AS/NZS 4600 and this research is now incorporated in the revised edition. The new areas in the DSM include shear, combined bending and shear, combined bending and compression, sections with holes and inelastic reserve capacity. Further, the prequalified sections now include most sections with longitudinal web and flange stiffeners based in part on Australian research on high strength sections with multiple stiffeners. New areas in the Australian/New Zealand Standard include extension of Section 8 Testing to design based on testing, Section 9 Design for Fire, Appendix B Methods of Analysis including advanced analysis, and Appendix D Buckling moments and stresses for local, distortional and global buckling. Revisions of design rules for net section tension and block shear rupture at bolted connections based on Australian research, inclusion of oversize and slotted holes, and screwed connections in tension and shear now are also included. The paper includes the research basis of the latest revisions with the supporting references.

DSM for Web Crippling under Two-Flange Conditions, Pedro Natário, Nuno Silvestre, and Dinar Camotim

This paper summarizes recent investigations on the development of Direct Strength Method (DSM) for the design of cold-formed steel beams under two-flange (TF) loading against web crippling failure. Recently, the authors proposed a new approach to predict the web crippling failure load of cold-formed steel beams under External Two Flange (ETF) and Internal Two Flange (ITF) loadings using DSM. Firstly, existing experimental test data are summarized and then the accuracy of North-American Specification (AISI 2012) and Eurocode 3 (CEN 2006) provisions is briefly assessed. In order to obtain additional information on the web crippling behavior of each test specimen, non-linear numerical results are obtained. Since the calibration of the DSM-based formula involves the previous calculation of (i) elastic buckling load and (ii) plastic load, two procedures are presented. Buckling loads are determined using the GBTWEB software, intentionally developed for this purpose, while plastic loads are calculated using analytical expressions based on yield-line models. By adopting a non-linear regression, the coefficients of DSM-based formulae are determined using a set of 128 (ETF) and 130 (ITF) test results and the corresponding estimates of buckling and plastic loads. The DSM-based formulas for ETF and ITF web crippling design are successfully proposed and the resistance factors (LRFD) obtained are φ=0.81 (ETF) and φ=0.75 (ITF).

Distortional Buckling Experiment on Cold-formed Steel Lipped Channel Columns with Circle Holes under Axial Compression, YAO Xingyou, GUO Yanli, NIE Zhen

The objective of this paper is to research the distortional buckling mode and load-carrying capacity of cold-formed thin-walled steel columns with circle holes in web. Compression tests were conducted on 26 intermediate length columns with and without holes. The test members included four different kinds of circle holes. Test results show that the distortional buckling occurred for intermediate columns with holes and the strength of columns with holes was less than that of columns without circle hole. The ultimate strength of columns decreased with the increase of the total transverse width of hole in cross-section of members. For each specimen, a shell finite element Eigen-buckling analysis and nonlinear analysis was also conducted. Analysis results show that the holes can affect on the elastic buckling stress of columns. The shell finite element can be used to model the buckling modes of columns with holes and analyze the load-carrying capacities of members with holes. The comparison on ultimate strength between test results and calculated results using Chinese code GB50018-2002, North American specification AISI S100-2016 and nonlinear Finite Element method was made. The calculated ultimate strength show that results predicted with AISI S100-2016 and analyzed using finite element method are close to test results. The calculated results using Chinese code is higher than test results because Chinese code has no provision to calculate the ultimate strength of members with holes. So the calculated method for cold-formed steel columns with circle holes was proposed. The calculated results using this proposed method show good agreement with test results and can be used in engineering design of cold-formed steel columns with circle hole.

Industrial Cold-Formed Steel Rack Column Base Fixityand Strength, Francesc Roure, Teoman Peköz, M Rosa Somalo, Jordi Bonada, M Magdalena Pastor, Miquel Casafont, James Crews

This paper summarizes the testing done at the Universitat Politècnica de Catalunya, Barcelona, Spain and the possible use of the results in design for column base stiffness and strength. The test setup and procedure are adopted in the European rack design standards.

Design of Industrial Cold-Formed Steel Rack Upright Frames for Loads in Cross-Aisle Direction, Francesc Roure, Teoman Peköz, M Rosa Somalo, Jordi Bonada, M Magdalena Pastor, Miquel Casafont

This paper summarizes research on the cross-aisle stiffness and strength of industrial cold-formed steel rack upright frames for loads in cross-aisle direction. Tests were carried out at the Universitat Politècnica de Catalunya, Barcelona, Spain on joints as well as entire upright frames. A possible rather simple analysis procedure is developed and described.

Characterizing the Load Deformation Behavior of Steel Deck Diaphragms, P. O'Brien, S. Florig, C. D. Moen, M. R. Eatherton

Lateral loads flow through a building's horizontal roof and floor diaphragms before being transferred to the vertical lateral force resisting system (e.g. braced frames, moment frames or shear walls). These diaphragms are therefore a critical structural component in the resistance of lateral loads. A review of the literature shows that a large number of experimental programs have been performed to obtain the in-plane load-deformation behavior of steel deck and concrete on steel deck diaphragms. The tested diaphragm behavior was found to be dependent on a set of factors including loading protocol, fastener type, fastener size and spacing, and more. There does not currently exist a single, unifying review of these diaphragm tests and their relevant results. A research program is being conducted to collect and consolidate the available literature about tested steel deck diaphragms and their results. A database has been created that includes over 450 tested specimens with more than 130 cyclic tests. In addition, an effort is made to characterize diaphragms' load-deformation response as grouped by sidelap and support fastener type. The test programs and results collected into this database as well as the characterization of diaphragm behavior are discussed in this paper.

Measured geometric imperfections for Cee, Zee, and Built-up cold-formed steel members, X. Zhao, B. W. Schafer

Geometric imperfections play an important role in the performance and behavior of cold-formed steel members. The objective of this paper is to present recent results from measurements of cold-formed steel members conducted by a laser scanner. The measurements provide complete and precise three-dimensional point clouds of the specimens and can be processed to determine dimensional variations as well as variations within the plates. Processing of the data can range from simple: e.g., mean lip length, to complex: e.g., modal decomposition magnitudes of the measured imperfections. Three different shapes of cold-formed steel members are selected for study: Cee, Zee, and built-up sections comprised of back-to-back Cee's. Realized dimensions of the studied cold-formed steel members are statistically explored providing mean and standard deviation and correlation data amongst the dimensions (flange width, lip length, flange-to-lip angle, etc.) can be readily performed. In addition, global (bow, camber, and twist) imperfections and cross-section Type I and Type II plate imperfections are determined from the scanned specimens. Modal imperfections decomposed into local, distortional, and global can also readily be calculated. The paper aims to demonstrate the worth of performing the three-dimensional geometric imperfection scanning and to provide useful data for simulations of cold-formed steel members. In the future it is anticipated that a systematic study of member imperfections could be used to provide definitive characterizations to help enable geometric imperfection selection in new analysis-based design approaches.

Experimental Investigation of the Effect of Screw Fastener Spacing on the Local and Distortional Buckling Behavior of Built-Up Cold-Formed Steel Columns. David C. Fratamico, Shahabeddin Torabian, Kim J. R. Rasmussen, Benjamin W. Schafer

This paper addresses an ongoing experimental and computational effort on the buckling and strength of built-up cold-formed steel (CFS) columns. Specifically, two 6 in. (152 mm) deep lipped channel sections (i.e. the 600S137-54 and 600S162-54 using AISI S200-12 nomenclature) are studied here in a back-to-back, screw-connected form and were chosen for their local and distortional slenderness to study the effect of fastener spacing and layout on local and distortional buckling and collapse behavior. Thirty column tests are completed with concentric loading. The screw spacing is varied from L to L/6, where L is the column length, with and without varying lengths of End Fastener Groups (EFG), which are a prescriptive layout of fasteners at the ends of built-up columns that is required by AISI S100-12 and is intended to insure end rigidity and increase composite action. Results yield two general types of deformation modes: compatible (where the connected webs conform to the same buckling shape) and isolated stud buckling. Buckling loads and half-wavelengths of deformation are shown to be affected by
the tighter screw spacings. EFGs increase compatibility of buckling, but prove to be an inefficient (costly) method of fastening studs together. Future work includes expanding the design methods for built-up CFS columns to explicitly account for local and distortional buckling behavior of the built-up section, and to develop efficient numerical tools supporting a new design method under development.

Advanced modeling of cold-formed steel walls under fire, J.C. Batista Abreu, N. Punati, K. R. Prasad, B.W. Schafer

This paper discusses an advanced finite element model able to simulate the structural response of cold-formed steel walls during standard fire tests. The model includes experimental thermo-mechanical properties of materials, geometric imperfections, and temperature distributions on studs and sheathing boards. The model is capable of reasonably predicting the thermal bowing of walls, and estimating the shape, size and amount of joint openings between gypsum boards over time of fire exposure. Numerical results validated with experimental data indicate that the maximum out-of-plane displacements due to thermal gradients occur near the wall mid-height. Early in the heating process, joint openings develop on the exposed side of walls due to thermal bowing and contraction of gypsum boards at elevated temperatures, potentially altering the heat transfer and affecting the fire resistance of the entire system. Future work aims to utilize high fidelity modeling to study the response of load bearing cold-formed steel systems subjected to fire, and optimize their fire

resistance.

Seismic Modeling and Incremental Dynamic Analysis of the Cold-formed Steel Framed CFS-NEES Building, J. Leng, S.G. Buonopane and B.W. Schafer

The objective of this paper is to present seismic modeling of a two-story cold-formed steel (CFS) framed building. The selected building, known as the CFSNEES building, was designed to current U.S. standards and then subjected to full-scale shake table tests under the U.S. National Science Foundation Network for Earthquake Engineering Simulation (NEES) program. Test results showed that the building's stiffness and capacity was considerably higher than expected
and the building suffered only non-structural damage and no permanent drift, even at maximum considered earthquake (per ASCE 7 and the selected California site) level. Past modeling, including that of the authors, largely focused on nonlinear hysteretic modeling of the shear walls. The test results indicate that additional building elements must be considered to develop an accurate characterization of the strength, stiffness, and ductility of the building. Advanced 3D models were developed in OpenSees to accurately depict the lateral response and included all structural and non-structural framing and sheathing, explicit diaphragm modeling, and nonlinear boundary conditions to capture bearing load paths This paper details the modeling techniques adopted and typical results including comparison with experiments. The impact of the various modeling assumptions on the results is also explored to provide a measure of system sensitivity. In addition, incremental dynamic analysis was performed on the building model and the results post-processed consistent with the FEMA P695 protocol. For the CFS-NEES building, designed to current standards, results indicate that the advanced model predicts an acceptable collapse margin ratio. In the future, the modeling protocols established here provide a means to analyze a suite of CFS-framed archetype buildings and provide further insight on seismic response modification coefficients.

Full-scale experimental and numerical study about structural behavior of thin-walled cold-formed steel building affected by ground settlements due to land subsidence, Jose A. Ortiz-Lozano, Luis A. Hernández-Castillo, Martin Hernández-Marín, Jesús Pacheco-Martínez, Mario E. Zermeño-deLeón, Raúl Salinas-Salinas

Land subsidence phenomenon due to ground water withdrawal is a current problem in many places around the world, particularly in the shallows of Mexico. This causes ground differential settlements that affect structures, mainly dwellings and buildings based on reinforced concrete and masonry. Eventually, these structural materials do not exhibit an adequate performance beyond a certain level of angular distortion. This work presents the experimental and numerical results about a study regarding the performance of a full-scale thin-walled cold-formed steel building affected by angular distortions simulating ground differential settlements due to land subsidence. The experimental stage consisted in the design and construction of a laboratory facility (hydro-mechanical device) which is able to reproduce differential settlements in laboratory as well as the construction of a full-scale one story building over this device, in order to test the building to differential settlements. The numerical stage consisted in modelling the building in non-linear structural analysis software, considering all the geometrical and mechanical properties, such as rotational stiffness, moment-rotation curves (based on the direct strength method), etc. A numerical non-linear static pull-down analysis was performed producing several degrees of angular distortion simulating the same differential ground settlements that the full-scale building constructed over the experimental device. The experimental and numerical results show that the structural performance of the tested building was very suitable in terms of ductility, since the structure was able to support large angular distortions without suffering considerable damages. Lastly, using structures based on cold-formed steel would be suitable to reduce damages and guarantee structural safety in structures constructed in zones affected by ground settlement due to land subsidence.

Monotonic and Cyclic Backbone Response of Single Shear Sheathing-to-Cold-Formed Steel Screw-Fastened Connections, F. Tao, R. Cole, C.D. Moen

Monotonic and cyclic backbone load-deformation response models for single shear plywood, oriented-strand board, and gypsum board sheathing to cold-formed steel screw-fastened connections are developed with support from an experimental program. Connection strength, stiffness, and the probability of screw shear failure are correlated to fastener bearing strength of the two connected plies. Cyclic strength and stiffness degradation was negligible. Cyclic excursions resulted in increased connection stiffness from the screw bearing hardening the ply material and locking in the plies.

Progress in the Development ofASCE 41 for Cold-Formed Steel, Deniz Ayhan, Robert L. Madsen and Benjamin W. Schafer

The objective of this paper is to document progress on new cold-formed steel provisions for the forthcoming edition of ASCE 41, Seismic Evaluation and Retrofit of Existing Buildings. The current edition of ASCE 41 (2013) is weak with respect to the application of cold-formed steel and provides only limited information on cold-formed steel framed buildings, shear walls, members, and connections. The emphasis in this paper is on cold-formed steel framed shear walls, and the development of modeling parameters that characterize the backbone shear-deformation response, and acceptance criteria that provide allowable demand-to-capacity ratios (m-factors) for the shear walls based on a broad evaluation of existing data. Significant additional work has been developed to update ASCE 41; including, developing descriptions of benchmark buildings framed from cold-formed steel and how damage and deterioration is observed in these buildings. These descriptions are necessary in the evaluation process and exist for other building materials in ASCE 41 (2013), but not for cold-formed steel framing. In addition, modeling parameters and acceptance criteria are provided for individual cold-formed steel members in flexure and steel-to-steel connections. The paper provides a description of the collected experimental

data and the procedures employed for developing modeling parameters and acceptance criteria, and provides the developed factors in summary form as currently being finalized through the ASCE 41 balloting process. The long-term goal of this effort is to further enable performance-based seismic design for buildings framed from cold-formed steel.

Stability analysis of thin-walled members with curved cross-section parts: inelastic behavior, D. Jobbágy, S. Ádány

In this paper the buckling behavior of thin-walled members with cross-sections with curved parts is investigated. Due to the curved parts, shell-like buckling is a potential mode of failure. The objective of the research is to understand whether shell-like buckling behavior might be governing in practical cold-formed steel members. For this aim, numerical studies have been carried out, involving linear buckling analysis as well as nonlinear analysis with imperfections, by considering various cross-sections. Based on the results it is concluded that shell-like behavior might be critical in certain cases.

Design method for cold-formed thin-walled steel beams with built-up box section, Ying-Lei Li, Yuan-Qi Li

Built-up sections has been extensively used in cold-formed thin-walled steel structures. The structural behaviour and moment capacity of built-up box beams, which is consisted of nested C and U-sections, are the major concerns in this paper. A finite element model for built-up box beams was firstly developed and validated by existing test results. The effects of screw configuration and the global buckling behaviour of built-up box beams were investigated by parametric analysis. Then, the simple superposition method and equivalent cross-section method were introduced and adopted to estimate the moment capacity of built-up box beams bending about major or minor axis. Finally, a comparison was made between the predicted capacity and the numerical analysis results and the reasonability of these methods was assessed.

Material properties of cold-rolled thin-walled steel plates at elevated temperatures, Zhen Nie, Yuanqi Li

It is highly important to clarify the high temperature mechanical properties in the design of cold-formed steel structures under fire condition due to the unique deterioration feature in material properties under fire environment and associated reduction to the mechanical performance of members. This paper presents the material properties of coupons cut from raw cold-rolled thin-walled steel plates at elevated temperatures. A set of high temperature extensometer with a range of 12.5mm relative to 50mm gauge was employed in the experiments, which could collect more displacement data between the gauge scope before the coupon fail. The coupons were extracted from original cold-rolled plates of GR340, GR410 and G550 steels with thickness of 1.0mm and 1.2mm, and a total of 50 tensile tests were carried out by steady state test method for temperatures ranged from 20 to 700°C. Based on the tests, material properties including the yield strengths, ultimate strengths, the elasticity modulus and the stress-strain curve were obtained. Meanwhile, the ductility of cold-formed steel plates were discussed. Finally, the temperature-dependent retention factors of all the material properties were compared to those provided by design codes and former researchers.

Behaviour of cold-formed steel trusses with concentric and eccentric joint arrangements using the Howick Rivet Connector, A. Ahmadi, C.L. Yee, H.J. Shepherd, G.C. Clifton, R. Das and J.B.P. Lim

This paper considers the behaviour of a cold-formed steel truss system that uses a novel pinned connector for the joints, to be referred to as the Howick Rivet connector (HRC). Use of the HRC allows a pinned concentric joint arrangement to be formed, as well as the more usual eccentric joint arrangement used in tests described in the literature. However, with the concentric joint arrangement, it is necessary to remove part of the lips of the channel-sections being connected, thus creating a discontinuity in the lips. This paper assesses the effect of this discontinuity. Full-scale truss tests are first described. The trusses have span of 19.7' (6 m), depth of 5.9' (1.8 m) and length of diagonals of 7.5' (2.3 m); both pinned concentric and pinned eccentric joint arrangement are tested. It was shown that the mid-span deflection of the concentric joint arrangement in the elastic range is 1.6 times smaller than that of the eccentric joint arrangement; the overall failure loads, due to flexural torsional buckling of the diagonal members, were found to be similar, and were not influenced by removal of part of the lips of the channel-sections. To investigate the effect of removing the lips for the concentric joint arrangement, a series of truss panel tests were performed for which the length of the diagonals were 2' (0.61 m). Failure was found to be local buckling at the discontinuity where the lip was removed, providing an upper bound to the joint strength.

Web Crippling Strength of Cold-Formed Duplex Stainless Steel Lipped Channel-Sections with Web Openings Subjected to Interior-One-Flange Loading Condition, Amir M. Yousefi, James B.P. Lim, Asraf Uzzaman, Ying Lian, 'G Charles Clifton, Ben Young

Cold-formed stainless steel sections are becoming more widely used in the residential and commercial sectors due to their high corrosion resistance and high strength-to-weight ratio. However, their susceptibility to web crippling at points of concentrated loading is well-known to be an important design issue. In addition, web openings are also become popular, as they improve ease of installation of services. This paper presents the results of an investigation into the effect of web crippling on cold-formed duplex stainless steel lipped channel-sections, having such openings, under the interior-one-flange (IOF) loading condition. 742 non-linear elasto-plastic finite element analyses are undertaken, with web openings located either centred beneath the bearing plate or offset to bearing plate. The effect of the size of the web opening, length of bearing plate and location of the web opening is considered. Strength reduction factor equations are proposed, that can be used to take into account such openings in design.

AISI Standards Developed and Updated in 2015 and 2016, Helen Chen, Roger Brockenbrough, Richard Haws

During 2015 and 2016, AISI developed framing standards were consolidated and updated, the North American Specification was updated and reorganized in format, and two new test standards were published. This paper provides an overview of the reorganized standards and major changes, and a brief introduction to the newly developed test standards.

Advancing BIM for Cold-Formed Steel Structures, Adam Johnson, Roni Ramirez, Cheng Yu

This paper presents a research project aimed at advancing BIM for cold-formed steel (CFS) structures. The creation of the CFS family for Autodesk Revit is a handy solution for the lack of CFS members and information inside the Autodesk Revit libraries. Revit is one of the industry's standard software for producing building information models. To overcome the disadvantages of not having CFS members in Revit, this research project focused on two phases to reach completion. Phase one consisted of developing a BIM library of industrial standard CFS members such as studs, tracks, and channels. Parameters were added to the members so that more information would be provided with them. These parameters include, but are not limited to, all the characteristics of CFS such as its gross, effective, and torsional properties. Phase two of the project consisted of using the developed CFS library to create light framed building models in Revit. This paper presents the results of creating and using this CFS library to produce CFS structures in combination with industry standard software.

Reduced Order Models for Profiled Steel Diaphragm Panels, G. Bian, S. Torabian, B.W.Schafer

The objective of this paper is to provide progress on development and validation of reduced order models for the in plane strength and stiffness of profiled steel panels appropriate for use in structural models of an entire building. Profiled steel panels, i.e, metal deck, often serve as a key distribution element in building lateral force resisting systems. Acting largely as an in-plane shear diaphragm, metal deck as employed in walls, roofs, and floors plays a key role in creating and driving three-dimensional building response. As structural modeling evolves from two-dimensional frameworks to fully three-dimensional buildings, accurate and computationally efficient models of profiled steel panels are needed. Three-dimensional building response is increasingly required by ever-evolving structural standards, particularly in seismic design, and structural efficiency demands that the benefits of three-dimensional response be leveraged in design. Equivalent orthotropic plate models provide a potential reduced order model for profiled steel panels that is investigated in this paper. A recent proposal for the rigidities in such a model are assessed against shell finite element models of profiled steel panels. In addition, the impact of discrete connections and discrete panels, as occurs in an actual roof system, are assessed when applying these reduced order models. Extension of equivalent orthotropic plate models to elastic buckling and strength, in addition to stiffness, both represent work in progress, but initial results are provided. Examples show that equivalent orthotropic plate models must be used with care to yield useful results. This effort is an initial step in developing efficient whole building models that accurately incorporate the behavior of profiled steel panels as diaphragms.

An Archetype Mid-Rise Building for Novel Complete Coldformed Steel Buildings, S. Torabian, Z. Saneei Nia, and B.W. Schafer

This paper introduces an archetype mid-rise cold-formed steel (CFS) building that aids in assessing the limits of current structural solutions, particularly lateral force resisting systems, and also in the development of new CFS technologies. A unified archetype building provides a platform for comparing the performance of new lateral force resisting systems to existing ones. The study herein provides quantitative evaluation of the design limitations of a typical "complete" cold-formed steel building (i.e. only cold-formed steel based elements are used for all gravity and lateral force resisting systems) at different heights (4 through 20 stories) located in a high seismic zone. The primary focus is the seismic force resisting system, which is limited to shear wall systems detailed in AISI specifications. The archetype buildings are designed using ASCE7-10 for all required loads and load combinations; and the CFS framing systems are designed utilizing AISI specifications, particularly AISI-400-15. Limitations in the application of current specifications for designing mid-rise cold-formed steel buildings are provided, and the potential for further studies discussed.

Lateral-Torsional Buckling of General Cold-Formed Steel Beams, Robert S. Glauz

The design of unbraced cold-formed steel beams must consider lateral-torsional buckling due to the low torsional stiffness associated with open cross-sections. The American Iron and Steel Institute incorporated design equations for the critical elastic lateral-torsional buckling stress in the North American Specification for the Design of Cold-Formed Steel Members. These equations are based on elastic theory for singly-symmetric and doubly-symmetric sections. However, the equation for point-symmetric sections is only a rough approximation. Furthermore, there are no provisions for lateral-torsional buckling of non-symmetric sections, or sections oriented to nonprincipal axes. This paper investigates and develops a general formulation of the lateral-torsional buckling equation to broadly cover all cold-formed steel cross-sections.

A Combined Direct Analysis and Direct Strength Approach to Predict the Flexural Strength of Z-Purlins with Paired Torsion Braces, Michael W. Seek, Chris Ramseyer and Ian Kaplan

A series of 12 Base Tests for Z-section purlins with paired interior torsional braces and one flange attached to a flexible horizontal diaphragm are evaluated with the Direct Strength Method. Rather than use the conventional constrained bending stress approxima-

tion, a direct analysis philosophy is adopted where cross section stress distributions are calculated using a displacement compatibility approach. With a flexible diaphragm typical of a standing seam roof system, these stresses can deviate substantially from the constrained bending approximation and can significantly impact predicted local and distortional buckling behavior. The displacement compatibility approach incorporates estimates of load imbalances and second order effects that result from the standard base test procedure. Predicted local and distortional buckling strength shows good correlation to tested strength.