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Abstracts of Conference Papers for Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures 2018

On November 7th and 8th, 2018 the Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures, the 24th in the series of international specialty conferences, will be held in St. Louis, MO, 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.

Shear Resistance Mechanisms on Steel Sheet Shear Walls with Burring Holes and Cross-Rails, Yoshimichi Kawai, Kazunori Fujihashi, Shigeaki Tohnai, Atsushi Sato and Tetsuro Ono

Steel sheet shear walls with burring holes are employed in low and mid-rise buildings in seismically active regions. A configuration with burrs on the inside enables the thinner wall and omitting the machining of equipment holes. The effects of cross-rails which are generally designed to strengthen the bearing capacities of the studs, on 2.73~4.53m height shear walls were clarified by finite element analysis and experiments. Post-buckling behavior depends on tension fields restrained by the cross-rails. The formulas of the allowable strengths and the indexes of ultimate strengths were developed using the mechanisms.

Tensile Strength and Serviceability of Cold-Formed Steel Clip Angles, Wenying Zhang, Zhishan Yan, Mahsa Mahdavian, Mohamad Yousof and Cheng Yu

This paper reports the recent research findings of cold-formed steel clip angles in tension. The relevant experimental program and the proposed design methods are presented. The test program involved two phases of testing: Phase I of program focused on the pull-over strength of screw connections on the anchored leg of the clip angles, and Phase II of program concentrated on the tensile strength of the anchored leg of the clip angles within the service deflection limit. Design methods for predicting the pull-over strength as well as tensile strength within the serviceability deformation limit are proposed based on the test results and analytical analysis. The Allowable Strength Design safety factors and the Load and Resistance Factor Design, Limit State Design resistance factors are also produced to support the proposed design methods.

SDI Steel Deck on Cold-Formed Steel Framing Design Manual, Thomas Sputo

The First Edition of the SDI Steel Deck on Cold-Formed Steel Framing Design Manual is the first design manual that specifically addresses the design of steel deck on cold-formed framing. The design of the steel deck is similar to deck on heavier rolled beams or open web steel joists, but it requires attention to some different detailing and fastening methods. This Manual concentrates on these differences.

Web Bearing Capacity of Cold-Formed Ferritic Stainless Steel Unlipped Channels with Web Perforations under the End-Two-Flange (ETF) Loading, Amir M. Yousefi, James B.P. Lim and G. Charles Clifton

Laboratory and numerical evaluations on the web bearing capacity of unlipped cold-formed ferritic stainless steel channels are described in this paper. The channels considered have circular perforations in the web and are loaded under the end-two-flange (ETF) load case. A total of 387 results comprising 27 laboratory and 360 numerical results are presented. A nonlinear quasi-static finite element (FE) model was developed for the numerical investigation. An extensive parametric study is described to determine web bearing capacity reduction factors for different sizes of circular web perforations and cross-section dimensions; the circular web perforations are either centred or offset to the load and reaction plates. It is noted that no cold-formed stainless steel standard provides capacity reduction factors for any end-two-flange load case. The capacity reduction factor equations are first compared to reduction factors previously recommended for lipped cold-formed stainless steel channels. It is found that these existing equations are unreliable and unconservative for unlipped channels by as much as 11%. From both laboratory and finite element results, web bearing capacity design equations are proposed for both sections, with and without web perforations.

Web Crippling Behaviour of Cold-Formed Ferritic Stainless Steel Unlipped Channels Under Interior-One-Flange and End-One-Flange Loadings, Amir M. Yousefi, James B.P. Lim and G Charles Clifton

The web crippling strength of cold-formed ferritic stainless steel unlipped channels subject to interior-one-flange and end-one-flange loading is considered in this paper. A total of 144 results are presented, comprising 36 laboratory and 108 numerical results. These results cover the cases of both flanges restrained and unrestrained to the load and reaction plates. Unlike other work in the literature, the numerical analysis in this paper uses nonlinear quasi-static finite element analysis with an implicit integration scheme, which has advantages over static and quasi-static with an explicit integration scheme analyses, particularly for post buckling predictions of unlipped channels subject to web crippling. The laboratory and numerical investigations show current stainless steel design guidance to be too conservative. In terms of design standards, while no cold-formed stainless steel standard distinguishes between flanges restrained and unrestrained to the load and reaction plates, with each standard providing only one equation to cover both restrained and unrestrained, the web crippling strengths for the flanges unrestrained case were found to be higher than those predicted from SEI/ASCE-8 by as much as 24%. Also, the web crippling strengths for the flanges restrained case are shown to be higher than those predicted from equations found in the literature by as much as 48%. New web crippling design equations are proposed; the proposed equations are shown to be reliable when compared against laboratory and numerical results.

On the Effect of Web Stiffening of Cold-Formed Steel Thin-Walled Lipped Sigma Sections in Compression Members, Rashideddin Cheraghi and Hamidreza Mohammaedzadeh

Cold-formed steel cross sections are high strength thin-walled profiles which are highly prone to local and distortional instabilities. Stiffening techniques are utilized in the industry as a solution to enhance local and distortional buckling strengths. The sigma section is that channel section which its web pused inward for the stiffening reason. In this research, the effect of side sway of the web (d_x) on the buckling behavior of lipped sigma sections is investigated. The results demonstrate that stiffening inclined components of the web in lipped sigma sections for the d_x up to 0.5512” (14 mm) act as a stiffener and change the dominant mode of the cross section from the local buckling the non-stiffened web to the distortional buckling for the stiffened web, and as this value rises, more reduction in the formation of local buckling in the web can be observed, but for the amount more than 0.5512” (14 mm), these components of the web act as an independent element and constrain the vertical parts of the web and local bucklingof sub-elements of the web is the dominant mode. Also under a parametric study, the effect of d_x on the Euler-local and distortional buckling strenghts and influential parameters on them is investigated and d_x value or strengths and influential parameters on them is investigated and d_x value for an optimum design is computed. Outcomes demonstrate that the more rise in the amount of dx augments the Euler-local and distortional buckling strengths and the optimum value of d_x is 0.3937” (10mm) for the target lipped sigma section.

Transverse Shear Stiffness of Bolted Cold-Formed Steel Storage Rack Upright Frames with Channel Bracing Members, Nima Talebian, Benoit P. Gilbert, and Hassan Karampour

Accurately evaluating the transverse shear stiffness of cold-formed steel storage rack upright frames is crucial to calculate the frame elastic buckling load, perform earthquake design and serviceability checks. This is especially essential for high-bay racks, which are subjected to large second-order effects, and racks supporting the building enclosure, which are exposed to transverse wind loads. The shear behaviour of these frames is poorly understood and experimental testing is usually required to measure their stiffness. Previous studies have shown that Finite Element Analyses (FEA), solely using beam elements, fail to reproduce experimental test results and may overestimate the transverse shear stiffness by a factor up to 25. In this paper, a commercially used upright frame, with either bolted lip-to-lip or back-to-back channel section bracing members, has been modelled using shell elements. The model is verified against available experimental data and found to accurately predict the experimental shear stiffness with an average error of 7%. Based on the verified FE model, the factors contributing to the frame shear deformation are quantified. The different frame deformations imposed by the test set-ups in the European (EN15512) and Australian (AS4084) standards are both considered. The effects of the bracing lay-out, the bolt bending, local deformations of the uprights and bracing members at the connections on the performance of the upright frames are quantified and discussed.

Biaxial Bending of Cold-Formed Steel Storage Rack Uprights – Part I: Parametric Studies and Response, Nima Talebian, Benoit P. Gilbert, Cao Hung Pham and Hassan Karampour

This paper first introduces an advanced finite element model to determine the biaxial bending capacity of cold-formed steel storage rack upright sections. The model is found to accurately predict published experimental results with an average predicted to experimental capacity ratio of 1.03. Second, the validated model is used to run parametric studies and analyse the biaxial response of slender, semi-compact and compact unperforated storage rack upright cross-sections. Analyses are run for local, distortional buckling failure modes. Nine biaxial bending configurations are analysed per cross-section and buckling mode. Results show that a nonlinear interactive relationship usually governs the biaxial bending of the studied uprights. This relationship is discussed in some details and analysed for the different failure modes and considered cross-section slenderness.

Biaxial Bending of Cold-Formed Steel Storage Rack Uprights - Part II: Design Methods, Nima Talebian, Benoit P. Gilbert, Cao Hung Pham and Hassan Karampour

This paper uses the results from the parametric studies reported in the companion paper to verify the accuracy of (i) the biaxial bending linear interaction equation used in international design Specifications and (ii) different forms of published direct strength method (DSM) equations. The latter forms consist of the classical DSM equations and considering the inelastic reserve capacity, with and without an extended range of the cross-sectional slenderness. The verifications are made for local and distortional buckling modes. Results show that the linear interaction equation overestimates the biaxial bending capacity. For all buckling modes, the DSM results in better predictions, especially when the inelastic reserve capacity is considered. The appropriate form of the DSM to predict the biaxial capacity of unperforated cold-formed steel storage rack uprights is discussed. Future work is also mentioned in the paper.

The Design and Development of Lightweight Composite Panels for Rigid Wall Shelters, Jeremy J. Artman and Cheng Yu

The paper presents a research effort aimed at developing a stronger, lighter, and more economic shelter for both military and civilian use. Reported herein are the research results on developing solid wall panels using cold-formed steel corrugated sheathing and members, as well as polyurethane spray foam for insulation. This research includes calculating uniform load density, determining the overall strength of the panel, and investigating the flexural strength of the roof panels. Research incorporated different connection methods, with varied stud spacing, to determine the safest design for the new mobile facilities. Previous research has shown that cold-formed steel corrugated sheathing performs better than thicker flat sheathing of various construction materials, with screw and spot weld connections. Full scale shear wall tests on this type of shear wall system have been conducted, and it was found that the corrugated sheathing had rigid board behavior before it failed in shear buckling in sheathing and sometimes simultaneously in screw connection failures.

Influence of Fire on the Shear Capacity of Cold-Formed Steel Framed Shear Walls, M. S. Hoehler and B. Andres

This paper presents experimental investigations of the performance of common lateral force-resisting systems used in cold-formed steel construction under sequential thermal (fire) and mechanical (earthquake) loading. Wall specimens with gypsum-sheet steel composite sheathing, Oriented Strand Board (OSB) sheathing, or steel strap bracing were tested. The results demonstrate that the lateral capacity of wall systems can be reduced via exposure to fire. Additionally, fire performance of wall systems can be affected by pre-damage to the fire resistive components that provide fire protection to these walls. The results are useful for fire compartmentation design when significant lateral deformation of a building is anticipated and post-fire assessment to repair or replace a structure. The study represents a step toward developing fire fragility functions for cold-formed steel framed shear wall systems to enable performance-based fire design.

Strength of Cold-Formed Steel Clip Angle in Combined Bending and Shear Loading, Cheng Yu, Zhishan Yan and Wenying Zhang

Thin-walled cold-formed steel (CFS) clip angles have been commonly used for connecting CFS framing members or attaching CFS members to the major building structure. The implementation of clip angles involves consideration of ultimate strength for combined bending moments and shear forces. Therefore, a test program of CFS clip angle was recently conducted to investigate the behavior and strength of cold-formed steel clip angle subjected to combined bending moments and shear forces at different boundary conditions. The research included connection tests on clip angle. The testing method was adopted from the AISI S914 Test Standard for Joist Connectors Attached to Clod-Formed Structural Framing. This paper presents the details of the test program, test results as well as recommendations for CFS clip angle configurations.

Behavior of Cold-Formed Steel Metal Industrial Buildings, Adrianna M. Early, M. Ebrahim Mohammadi, Richard L. Wood and Kara D. Peterman

This paper presents research focused on understanding the observed behavior of cold-formed steel (CFS) metal buildings during Hurricane Harvey, which made landfall Friday, August 25, 2017 between Port Aransas and Port O'Connor, Texas. Through the Geotechnical Extreme Event Reconnaissance (GEER) association (funded by the National Science Foundation) a team of structural engineers and researchers performed rapid and detailed assessments of structural damage caused by the hurricane. The National Science Foundation gathered photographs, damage assessments sheets, and three-dimensional laser point cloud data of severely damaged cold-formed steel industrial buildings. The Port Aransas County Airport experienced severe damage to several cold-formed steel small aircraft hangars. The failure of one of these hangars is the basis for this investigation. The laser point cloud data was utilized to create a model of a hangar structure in MASTAN2. Multiple analyses were completed in MASTAN2 to determine the failure mode and damage propagation mechanisms. Also, analyses were completed to determine the behavior of the undamaged structure and the structure after loss of the hangar doors. The objective of this research is to determine the behavior of cold-formed steel structures under extreme loads to form recommendations for future construction. Furthermore, this work is among the first to use post-disaster data to examine structural cold-formed steel performance.

Critical Design Criteria for Standard, Truncated, and Parallel Chords Cold-Formed Steel Trusses, Maelle van Thienen, Johannes Dimyadi, James B. P. Lim and G. Charles Clifton

The design of cold-formed steel trusses can be a very complicated and long repetitive process involving up to 28 load combinations added to serviceability checks depending on the design standards being used. This process is particularly tedious if a near optimal solution is required. Additionally, the risk of introducing human errors is usually quite high as it is a process often done by hand. FRAMECAD Structure is a niche software solution born from the desire to provide a complete solution for constructing with cold-formed steel by a company selling roll-forming machines. FRAMECAD Structure specialises on automating the calculations and design of cold-formed steel framed panels, trusses and joists with minimal user input. However, computational-oriented software applications are often not optimised for performance, hence the inefficiency in obtaining a design solution, i.e. the proposed solution is either not optimal or takes a considerable time to compute. To provide guidelines on the design of cold-formed trusses, this research uses FRAMECAD Structure to study which design parameters are critical and what impact they have on optimising the design outcome.

Effect of Connection Details on the Cyclic Behavior of Nestable Screw Sidelaps, S. Torabian, H. Folk, and B.W. Schafer

Sensitivity of nestable screw sidelaps to screw installation details has been experimentally explored via cyclic push out tests, herein. The cyclic behavior of sidelaps has been recently incorporated in the high fidelity modeling and seismic evaluation of the steel deck diaphragm in rigid wall flexible diaphragm buildings, where unzipping a sidelap could significantly reduce the seismic performance of the whole diaphragm. A total 24 monotonic and cyclic sidelap tests have been performed in the Thin-Walled Structures Laboratory at Johns Hopkins University. Two different screw edge distances, three different deck thicknesses (i.e. 18 gage 20 gage, and 22 gage), and two different screw sizes were included in the test matrix. The screws were installed close to the edge and far from edge, where the typical 1.5d edge distance limitation in the design specification was not satisfied for the screws installed close to the edge. Both monotonic and cyclic test results have shown that the strength of the sidelap connection can be correlated to edge distance and screw installation details. Maximum 25% and 19% difference in the ultimate strength of the screw sidelaps were observed in monotonic and cyclic tests, respectively. The rest results were compared to the sidelap strengths in the literature and potential changes to the sidelap strength predictions and installation methods were discussed.

Cyclic Performance and Behavior Characterization of Steel Deck Sidelap and Framing Connections, S. Torabian, D. Fratamico, K. Shannahan and B.W. Schafer

A wide variety of steel deck sidelaps and framing connections have been experimentally studied to characterize the cyclic performance required in seismic evaluation of steel deck diaphragms. This study intends to provide cyclic test results of common non-proprietary steel deck connections including screw nestable and top arc seam sidelaps; and powder actuated fasteners, arc spot weld, and arc seam weld framing connections. The cyclic behavior of sidelaps and framing connections has been recently augmented in the high fidelity finite element simulations to evaluate the seismic behavior of the steel deck diaphragm in rigid wall flexible diaphragm buildings, where inelasticity and ductility of the building system are intended to be derived largely from the diaphragm and the connections. A total of 24 sidelap and 36 framing (structural) connection tests have been performed in the Thin-Walled Structures Laboratory at Johns Hopkins University by NBM Technologies. The connection test results have been used to parameterize a nonlinear hysteretic spring element (i.e. utilizing the Pinching04 material model) applicable to modeling of the connections in high fidelity steel deck diaphragms. Finally, the test results have been compared to AISI 310 and SDI-DDM04 connection strength and stiffness predictions. This experimental program is a task within a larger effort, i.e. “Advancing Seismic Provisions for Steel Diaphragm in Rigid Wall-Flexible Diaphragm Buildings” by NBM Technologies. The object of the larger effort is to validate alternative seismic design provisions for conventionally designed steel diaphragms in RWFD buildings.

Experimental Study on Uplift Capacity of Purlins Considering Restraints from Standing Seam Roof Systems, Wei Luan and Yuanqi Li

A total of 32 specimens of single-span purlin roof assemblies considering uplift wind load were tested to investigate the structural behavior of cold-formed steel purlins with one flange fastened to standing seam roofs. Failure modes and failure loads of purlins with different parameters were obtained. Full finite element models, incorporate purlins, clips and standing seam roof panels, were developed, and the analysis results were consistent to a high degree with the test results. Using the same element type and material model, the rotational restraint of test roof systems and corresponding influence factors were investigated by finite element models. Finally, using the rotational restraint rigidities and comparing with the test results, the lateral restraint of test roof systems were also studied through a simple finite element model incorporates pure the purlin and presents the rotational restraints and lateral restraints by rotational and lateral springs. It is shown that the standing seam roofs do provide some extent of rotational restraints and lateral restraints to purlins at the connection points, especially for purlins without sag rod.

Cold-Formed Steel Framed Shear Wall Database, Deniz Ayhan, Samuel Baer, Colin A. Rogers and Benjamin W. Schafer

The objective of this paper is to provide an introduction to a recently compiled database of cold-formed steel framed shear wall tests and demonstrate the application of this database for improving the understanding and modeling of cold-formed steel framed shear walls. Over the last 20 years a substantial number of cold-formed steel framed shear walls have been tested under monotonic and cyclic conditions. These tests provide the support for the cold-formed steel framed shear wall provisions provided in the North American Standard for Cold-Formed Steel Structural Framing (AISI S240-15), the North American Standard for Seismic Design of Cold-Formed Steel Structural Systems (AISI S400-15), and the Seismic Evaluation and Retrofit of Existing Buildings standard (ASCE41-17). The initial version of the database was assembled during the development of ASCE41-17. The database has recently been expanded to include additional tests, additional complete cyclic information from tests, additional fields regarding limit states and code predictions, and placed in a standardized format. The database consists of a central Excel spreadsheet, ordered plain text files for each individual test, and custom Matlab code for reading, processing, and plotting any desired subset of the database. In addition, a Matlab tool has also been written that can convert selected test response to single degree of freedom hysteretic model response, as might be employed in OpenSees or other nonlinear structural analysis engines. The information in the database is summarized herein, along with commentary on current code provisions, and areas of potential improvement and need.

Sustainability of Modular Lightweight Steel Building from Design to Deconstruction, Ornella Iuorio, Loredana Napolano, Luigi Fiorino and Raffaele Landolfo

The increasing concerns over population growth, depletion of natural resources and global warming as well as catastrophic natural events is leading the international scientific community to envisage sustainability as a crucial goal. The built environment plays a key role on the triple bottom line of the sustainable development - Planet, People, Profit - because of several environmental, social and economic impacts produced by the construction sector. The acknowledged need to promote a sustainable building market is an international high-priority issue as underlined by the 2030 Agenda for Sustainable Development. Indeed one of its strategic objectives highlights to make cities and human settlement inclusive, safe, resilient and sustainable. In line with the 2020 Europe Strategy and the European 2050 Roadmap, energy efficiency and CO2 savings towards a low-carbon economy are regarded as ambitious objectives to be achieved for both new and existing buildings. Thus, controlling and reducing the environmental impacts of new constructions is fundamental.

In line with this, the “Energy efficient LIghtweight Sustainable SAfe steel construction” (ELISSA) research project financed under the European FP7 aimed to develop a modular Cold – formed steel system that is energy efficient and robust. This paper presents the life cycle analysis of the building developed as case demonstrator. It analyses the environmental impacts during both the construction and the deconstruction phase. This works provides a benchmark of the current possibilities offered by lightweight steel structures in the framework of sustainable constructions.

Fire Resistance of Cavity Insulated Light Gauge Steel Framed Walls, Anthony Deloge Ariyanayagam and Mahen Mahendran

Light-gauge steel framed (LSF) wall systems are made of cold-formed steel studs and tracks and lined with gypsum plasterboards. They are mostly cavity insulated to provide acoustic and thermal performance. Cavity insulation delays the temperature rise across the wall as it restrains the heat transfer. This delays the ambient plasterboard surface temperature rise and thus improves the insulation failure time of LSF walls. However, LSF walls are also used as load bearing walls. Having cavity insulation causes the fire side temperatures to increase rapidly, resulting in a higher temperature gradient across the stud depth. This leads to higher thermal bowing deflection and crack openings on the fire side plasterboard and exposing studs to higher temperatures. These effects reduce the fire performance of load bearing walls. However, most designers consider that cavity insulation is beneficial for all LSF wall configurations. Thus experimental and numerical studies were conducted to investigate the effect of cavity insulation in both load bearing and non-load bearing walls. Experimental study was conducted on four full-scale wall panels with and without cavity insulation. Fire test results showed that cavity insulation delays heat transfer and is beneficial for non-load bearing walls. However, cavity insulation significantly reduced the fire resistance of load bearing walls. Numerical study was then conducted to obtain the structural adequacy failure times for varying levels of applied loads. This paper presents the results of these studies including the stud failure times and temperatures. The results showed that the use of cavity insulation significantly reduced the fire resistance levels of load bearing walls.

New Web Crippling Design Rules for Cold-formed Steel Beams, L. Sundararajah, M.Mahendran and P. Keerthan

Lipped channel beams (LCBs) and SupaCee sections are commonly used as floor joists and bearers in the construction industry. SupaCee section is one of the cold-formed steel members, which is increasingly used in the building construction sector. It is characterized by unique ribbed web and curved lip elements, and is claimed to be more economical with extra strength than the traditional channel sections. These thin-walled LCBs and SupaCee sections are subjected to specific local and global failures, one of them being web crippling. Several experimental and numerical studies have been conducted in the past to study the web crippling behaviour and capacities of different cold-formed steel sections under different concentrated load cases. However, due to the nature of the web crippling phenomenon and many factors influencing the web crippling capacities, capacity predictions given by most of the cold-formed steel design standards are either unconservative or conservative. Hence both experimental and finite element studies were conducted to assess the web crippling behaviour and strengths of LCBs and SupaCee sections under ETF, ITF, EOF and IOF load cases. New equations were proposed to determine the web crippling capacities of LCBs and SupaCee sections based on the results from experiments and finite element analyses. Suitable DSM based web crippling design equations were also developed.

Design of Rivet Fastened Rectangular Hollow Flange Channel Beams Subject to Local Buckling, R. Siahaan, P. Keerthan and M.Mahendran

The innovative, rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new type of cold-formed steel section, proposed as an extension to the widely researched hollow flange beams. The hollow flange beams have garnered much interest in the past due to the sections having capacities more typically associated with hot-rolled steel sections. Various researches have been carried out to investigate the behavior of continuously welded hollow flange beams but little is known on the behavior of RHFCBs. The structural behaviour of the RHFCB is unique compared to other conventional cold-formed steel sections and its moment capacity reduces with rivet spacing. The current cold-formed steel design standards do not provide a calculation method to include the effects of intermittent fastening. In this research an extensive parametric study was conducted using validated finite element models to investigate the section moment capacity of RHFCBs. This paper presents the findings from the parametric study and proposes new design equations for the section moment capacity of RHFCBs in the Direct Strength Method format. The parametric study considers various slenderness regions, section dimensions and rivet spacing. In the new design equations, a reduction factor parameter is included to calculate the section moment capacity of RHFCBs at any rivet spacing up to 200 mm.

Localised Screw Connection Failures in Cold-formed Steel Roofing Systems, Mayooran Sivapathasundaram and Mahen Mahendran

Lightweight roofing systems made of thin and high strength steel roof sheeting and battens are commonly used in low-rise buildings. However, they often fail frequently at their screw fastener connections during wind storms due to inadequate connection capacities. Two localised failures, known as pull-through and pull-out failures at the screw fastener connections, have been the root cause for extensive loss of roofing systems under high wind uplift loads. Such premature connection failures often cause partial or even complete loss of steel roofing systems and severe damage to building contents. Therefore many experimental studies have been conducted to investigate the pull-through failures of roof batten to purlin/rafter connections and the pull-out failures of roof sheeting to batten and roof batten to rafter connections. The roof batten connections involve multiple (two or four) screw connections between the two bottom flanges of roof battens and rafters. This paper reports the details of experimental studies on one of the localised screw connections failures, the pull-out failures. More than 750 small scale pull-out tests were conducted for this purpose using a range of screw fastener sizes and many thicknesses of thin steel roof battens and purlins. This paper presents the important details of the experimental studies and the pull-out capacity data obtained from the tests. It then presents suitable design equations and capacity reduction factors to accurately determine the pull-out capacities of both single and multiple screw fastener connections commonly used in steel roofing systems. They can also be used for the screw fastener connections in steel wall cladding systems.

A Preliminary Study on Stainless Steel Hollow Flange Beams Featuring Lateral-Distortional Buckling, Shuang NIU, Zhidong ZHANG, Feng FAN

To explore the potential of using stainless steel structurally, extensive research has been carried out to study the structural behavior of stainless steel member as associated with the nonlinear stress-strain relationship. Hollow flange sections feature improved structural efficiency and a unique issue of web distortion. Steel hollow flange sections have been studied and commercially distributed (e.g. the very first HFB section and lately LSB section). As a proactive study, this paper investigates stainless steel hollow flange beams of double-symmetric section with numerical modeling and parametric analysis. The validity of the idealized FE model was verified with existing study on steel counterparts. Specifically, three alloys (S30401, S44330, S32101) and a series of sections and member spans were covered. Preliminary conclusions were drawn about the effects of material nonlinearity, work-hardening and lateral-distortional buckling on the member strengths. Performance of current design provisions (AS4100, AS/NZS4600, EC3, CECS410) were evaluated and it was found that Eurocode 3-1.4 beam design curve has a better overall prediction of the member strength.

Flexural Strength of Continuous-Span Z-Purlins with Paired Torsion Braces using the Direct Strength Method, Michael Seek

A procedure is presented to calculate the local and distortional flexural buckling strength of continuous span purlins with paired torsion braces using the Direct Strength Method. Displacement compatibility is utilized to determine the forces interacting between the purlin, the flexible diaphragm and the torsion braces. The biaxial bending and torsion effects caused by this interaction are superimposed, and the actual distribution of stresses within the cross section are calculated at critical locations along the span. With this distribution of stresses, a finite strip buckling analysis is performed to determine the local and distortional buckling strength.

In current design practice, results from a simple span Base Test are extrapolated to multi-span systems using a constrained bending stress distribution. In previous work, a variation of the presented method was compared to simple span base test results with good correlation. In this paper, the simple span stresses are compared to the stresses of continuous span systems. Significant, although typically conservative differences in the stress distributions and, as a result the predicted flexural strength, are observed in the comparison between simple span and multi-span systems. Additionally, significant changes in the distribution of stresses are observed as roof slope effects are considered. Increases in the flexural strength with increasing roof slope are reported and compared to the strength predicted by the current base test method.

Stressed Skin Design of Steel Sheeting Panels – Part 1: Shear Resistance and Flexibility of Screw Lapped Joints
A.M. Wrzesien, J.B.P. Lim, I.A. MacLeod and R.M. Lawson

The shear resistance and flexibility of a steel roof diaphragm depend largely on shear resistance and slip flexibility of the single screw lap joint. In this paper, screw connections relevant to modern roof construction are investigated. The tests provided experimental values of shear/tearing resistance and joint flexibility of seam connections, cladding/purlin connections and purlin/rafter connections. The novel aspects of the experimental research include investigation of the behaviour of shear connections in 0.5mm thick sheeting and thick-to-thin connections in S550 high tensile steel. Overall, six series of tests were conducted and each test was repeated five times in order to demonstrate a scatter of test results. Test results were examined against existing semi-empirical formulas for predicting the shear resistance of screw joints. It was demonstrated that the design equation presented by Toma et al. (1993), without the additional condition included in Eurocode 3, offers the closest prediction in terms of joint shear resistance. In terms of joint flexibility, it was demonstrated that existing formulas developed for bolted connection (Zadanfarrokh and Bryan (1992) and Dubina and Zaharia (2006)) can be successfully used for screw connections. The flexibility reduction factor npf=0.4 was also proposed to take account of perfect fit screw connections.

Stressed Skin Design of Steel Sheeting Panels – Part 2: Shear Panels with Sheeting Fixed on All 4 Sides, A.M. Wrzesien, J.B.P. Lim, I.A. MacLeod & R.M. Lawson

In this paper, the strength and stiffness of different roof panels were investigated, in order to establish their ability to act as in-plane diaphragms for stressed skin design of cold-formed steel portal frames. A total of 6 roof panels, approximately 3 x 3m, were examined by testing with sheeting profiles fixed on 4 sides. A variety of sheeting profiles in two industry standard thicknesses of 0.5 and 0.7mm were tested, all using top-hat shaped purlins fixed with self-drilling, self-tapping screws. The experimental strength and stiffness of each panel were then compared against existing design methods. The Finite Element Analysis (FEA) modelling techniques were also presented and validated against series of full-scale tests. The FEA results have shown that the 'true' level of loading transferred via shear connector screws was on average 13% lower than that assumed by standard design methods. On the contrary, seam connections failure, according to FEA results, have governed a design in all of the analysed cases and the analytical method overestimated shear resistances of the panels by 45% and 35% in case of 0.5mm and 0.7mm thick sheeting profiles respectively. It was demonstrated that FEA results have represented the upper bound of experimental shear stiffness, with a very close prediction for 0.5mm thick sheeting profiles. Overall all, the tested panels demonstrated an average 41% greater flexibility then this predicted using FEA models.

Using Generalized Beam Theory to Assess the Behavior of Curved Thin-Walled Members, Nuno Peres, Rodrigo Gonçalves and Dinar Camotim

In this work, the first-order behavior of naturally curved thin-walled bars with circular axis, without pre-twist, is assessed with the help of the Generalized Beam Theory (GBT) formulation previously developed by the authors. With respect to the previous work, which dealt with simple cross-sections, the present paper presents a method to obtain the deformation modes for arbitrary flat-walled cross-sections. Despite the complexity involved in this generalization, the standard GBT kinematic assumptions are kept, since they are essential to (i) subdivide the modes in a meaningful way and (ii) reduce the number of DOFs necessary to obtain accurate solutions. It is shown that the curvature of the bar influences significantly the deformation mode shapes. Furthermore, a standard displacement-based finite element (FE) is employed to solve several examples that highlight the peculiar behavior of curved members. For validation and comparison purposes, results obtained using shell FE models are provided. Finally, the superiority of a mixed GBT-based FE format is demonstrated.

Study on Distortional Buckling of Cold-formed Stainless Steel Beams, Shuang NIU, Zhidong ZHANG and Feng FAN

In the current research, distortional buckling of cold-formed stainless steel open-section beams was investigated. Four-point bending tests of eight C-section stainless steel beams, made of S30401 alloy, were carried out with global and local buckling precluded by careful design of specimen and test rigs. A detailed finite element model based on ABAQUS was developed and verified against test data. Parametric study was carried out with the verified model, covering four types of sections (C, Z, SupaCee, and SupaZed), three stainless steel alloys (S30401, S44330, S32101), and a series of section slenderness. A convenient method to identify distortional buckling point in either experimental or numerical study was discussed. Existing design formula for stainless steel and steel structure were assessed with the available data. Revised formula based on Direct Strength Method was proposed.

Shake Table Testing for Seismic Response Evaluation of Cold-Formed Steel-Framed Nonstructural Architectural Components
Luigi Fiorino, Bianca Bucciero, Tatiana Pali, Ornella Iuorio and Raffaele Landolfo

The seismic response evaluation of cold-formed steel-framed nonstructural architectural components was investigated in an experimental campaign carried out within of the research study agreement between Knauf Gips KG and the Department of Structures for Engineering and Architecture of the University of Naples "Federico II". The main objective of this research was to investigate the seismic performance of drywall nonstructural systems, i.e. cold-formed steel-framed indoor partition walls, outdoor façade walls and suspended ceilings. The present paper deals with the dynamic shake table tests. The tests were carried out on two different typologies of prototypes (Type 1 and Type 2) for a total number of five specimens. The influence on seismic response of basic and enhanced anti-seismic solutions, corresponding to the use of fixed or sliding connections at the walls and ceilings perimeter, was investigated. The seismic response evaluation of the systems under investigation has been performed according to ICBO-AC156 code with different levels of increasing intensity. Test results have been analysed in terms of dynamic identification, dynamic amplification, and fragility curves. Test results highlight that enhanced solutions have a better seismic response than basic solutions and indoor partition walls have a higher seismic “fragility” than outdoor façade walls.

Finite-Element Analysis of the Eaves Joint of Cold-Formed Steel Portal Frames having Single Channel-Sections, Pouya Pouladi, John Ronaldson, George Charles Clifton, Jason Maxwell Ingham, Andrzej M. Wrzesien, Paul Milewski and James B.P Lim

A finite element model is described for the eaves joint of a cold-formed steel portal frame that comprises a single channel section for the column and rafters eaves connections. The members are connected to the brackets through both screws and bolts. Such a joint detail is commonly used in practice in New Zealand and Australia, where the function of the screws is to prevent slip of the joint during frame erection since the bolt holes are detailed for nominal clearance. The results of the finite element model are compared against two experimental test results. In both, the critical mode of failure is a combination of torsion of the eaves joint and shear failure of screws. It is found that at ultimate load, the bolts have not engaged i.e. they have slipped. It is shown that the stiffness of the joints can be accurately predicted from the equations of bolt and screw stiffness of Zaharia and Dubina (2000). Preliminary conclusions are that the finite element model can be capable of determing upper and lower bounds to the experimental failure load, and potentially can be used safely for design purposes.

Numerical Simulation of the Thermal and Mechanical Behavior of Cold-Formed Steel Composite Floor under Fire Conditions, Jixian Peng, Wei Chen, Jihong Ye and Zhengliu Wang

Cold-formed steel (CFS) building structures are generally acknowledged as green and industrialized buildings, and the fire resistance behavior has become an important issue. Previous studies were mainly to investigate the fire performance of load-bearing CFS walls lined with different panels. Based on the finite element (FE) software package, ABAQUS, this paper presented a numerical simulation on a new CFS channel joist – ALC (autoclaved lightweight concrete) composite floor under fire conditions. Finally, the present numerical simulation of CFS composite floor in fire was compared with previous full-scaled fire experiments of such floors. The results showed that the temperature progression of the CFS floor section was well predicted with acceptable accuracy. The time-dependent vertical deflection of the CFS floor was well described and the fire resistance time of CFS floor system was well predicted with an underestimation of less than 6% and an overestimation of less than 10%.

Screw and Pin Fastener Tests for Cold-Formed Steel, Brian S. Wilson, Fredrick R. Rutz and James R. Harris

Because of limited available information on strength and ease of installation of specific fasteners for a particular application to a steel deck diaphragm, a preliminary testing program comparing the shear strength of commercially available screws and gas-actuated shot pins was conducted by J.R. Harris and Company at the University of Colorado, Denter in 2018. A test was designed to explore the behavior and capacity of various fasteners, securing two and three pieces of sheet steel of various thicknesses together. Specimens were fabricated and load tested, with the sheet steel pieces in tension, so the fasteners were subject to shear. Four fasteners, in two rows of two, were used for all tests, with different end distances also being studied. Most of the tests were monotonic tension, and those results were used to develop a cyclic testing protocol for the best performing screw and shot pin.

Most limit states encountered were limited by tilting of the screw against the sheet steel in bearing, leading to a ductile failure. Fastener shear was encountered in a small percentage of cases. Results are compared to each other and to AISI calculated values.

Optimum Slot Weld Width for Cold-Formed Steel, Emilee A. Martin and Fredrick R. Rutz

Slot welds can be used for connections in cold-formed steel (CFS) structures. However, structural engineers will find AISI S100, “North American Specification for the Design of Cold-Formed Steel Structural Members” (AISI 2016) - which can be used for guidance in calculating structural capacity of many welds types - silent on this specific application.

Research at the University of Colorado Denver has been directed toward determination of the strength of slot welds in sheet steel. A comprehensive series of tests were performed to determine structural capacity and ductility of various slot weld widths using a metal inert gas welding (MIG) process. A slot weld connection between two pieces of sheet steel was designed, one with punched slots of various widths, and the other a blank piece to receive the weld. Weldability problems associated with slot welds of various widths on galvanized sheet steel were encountered. The testing program to investigate slot widths to address these concerns is reported upon.

A program of monotonic tension tests was conducted. This testing program built on 1979 research by Pekoz and McGuire at Cornell University for fillet welds on lap joint specimens. While AISI is silent on slot weld design criteria, the authors found certain slot widths were more advantageous than others.

Experimental Study of Apex Cconnection Stiffness and Strength of Cold-Formed Steel Double Channel Portal Frames, J. Peng, J. Bendit and H.B. Blum

Cold-formed steel portal frames are an increasingly popular structure in the housing and industrial sectors, and are commonly used for garages, sheds, and shelters. Longer span cold-formed steel portal frames are relatively new to the market, and as a result limited design guidance and recommendations exist, including the strength and stiffness of the connections. The apex connection stiffness affects the distribution of internal actions and deflections of a portal frame, and therefore, it is necessary to quantify the apex stiffness for use in design models to accurately determine the frame behavior. An experimental program was carried out on a series of twelve apex connections of portal frames composed of back-to-back lipped channels for the rafters and back-to-back lipped L apex brackets, which were connected by bolts through the webs. The channels had a depth of either 200 or 150 millimeters, and thickness of 1.5, 1.9, or 2.4 millimeters. The apex brackets were 2.4 millimeters thick, and the dimensions varied to match with the connecting rafter sections. The apex connection stiffness and strength were quantified, and the effects of rafter thickness and depth on the connection stiffness and strength were determined. The aim of this work is to quantify the apex connection stiffness of cold-formed steel portal frames composed of back-to-back channels and L-brackets to enable practicing engineers to accurately determine the internal actions and deflections of portal frames.

Behavior of Beam to Column Cold Formed Section Connections Subjected to Bending Moments, Maged T. Hanna, Mohamed M. El-Saadawy, Ghada M. El-Mahdy and Ehab H. A. H. Aly

Cold formed sections are often used in the construction of mid-rise buildings due to their high strength weight ratios, and fast erection. In these buildings, the connections between joists and studs are mainly simple connections. However, application of these sections can be extended to moderate span frames where connections between members are subjected to bending moments. Strength and stability of such frames depends to large extent on the behaviour of the connections between their members. Over the last twenty years, several researchers undertake tests on cold formed section connections subjected to bending moments. Major of them classify the connections as semi-rigid, but some suggested that as we reach the maximum capacity of the connected sections so we can consider it rigid.

Web Crippling of Cold-Formed High Strength Steel Square and Rectangular Hollow Sections under Two-Flange Loading Conditions, Hai-Ting Li and Ben Young

The web crippling behavior of cold-formed high strength steel (HSS) square and rectangular hollow sections under End-Two-Flange and Interior-Two-Flange loading conditions is studied. The cold-formed HSS tubular sections had nominal 0.2% proof stresses of 700 and 900 MPa. Finite element (FE) models were developed and validated against test results, showing the capability of replicating the experimental web crippling strengths, failure modes and load-deformation histories. Upon validation of the FE models, an extensive parametric study comprised 112 FE analyses was performed. The web crippling strengths obtained from the experimental and numerical investigations were compared with the nominal strengths calculated from the North American Specification, Australian/New Zealand Standard and European Code for cold-formed steel structures. The comparison results show that the nominal strengths predicted by the existing codified web crippling design provisions are either unconservative or overly conservative. Hence, new design rules are proposed for cold-formed HSS square and rectangular hollow sections by means of Direct Strength Method (DSM). It is shown that the modified DSM is able to provide reasonably good predictions.

Cold-Formed Ferritic Stainless Steel Tubular Sections under End-One-Flange Loading Condition, Hai-Ting Li and Ben Young

This paper presents experimental and numerical investigations of cold-formed ferritic stainless steel tubular sections under End-One-Flange (EOF) loading condition. A series of web crippling tests was conducted on cold-formed square and rectangular hollow sections of ferritic stainless steel grade EN 1.4003. The web crippling test results were used for the verification of the finite element (FE) model. Upon verification, a parametric study was performed thereafter. The codified web crippling design provisions in American, Australian/New Zealand and European standards for stainless steel structures were assessed. Improved web crippling design rules are proposed for cold-formed ferritic stainless steel tubular sections under EOF loading condition through modifying the design rules of the North American Specification and Direct Strength Method. It is shown that the modified web crippling design rules are able to provide accurate and reliable predictions.

Investigation on Shear Capacity for Screw connections of Cold-Formed Steel Framed Shear Walls with Steel Sheathing, Feng Ruoqiang, Ma Ying and Zhu Baochen

Experimental and numerical investigations were carried out to learn the shear capacities for screw connections of cold-formed steel framed shear walls with steel sheets for the base layer combined with gypsum wallboards for the face layer. The design methods of test specimens, the loading equipment and the data processing method were introduced. According the phenomenon of tests for multiple self-drilled screw connections, the loading-deformation curves, shear capacity and failure modes were testified. The influence of end distance of screw, edge distance of screw, diameter of screw, spacing of screw, thickness of steel sheets, thickness of gypsum wallboards, thickness of studs on shear behavior for connections were investigated. The finite element software ABAQUS was used to simulate the shear behavior of screw connections. A comparison between the numerical simulations and the test results showed a good agreement. This study can be applied to numerical simulations of seismic behavior of steel sheathed cold-formed steel framed shear walls.

Bearing Strength of Untightened Double-Shear Bolted Connections in Cold-Formed Steel Construction, Refat A. Bhuiyan, Lip H. Teh and Aziz Ahmed

This paper presents the experimental investigation of cold-formed steel double-shear bolted connections where both the bolt head and the nut are not in contact with the outer sheets. The inner sheet of each specimen is not constrained from out-of-plane distortion or bulging downstream of the bolt, and fails in bearing. Based on a series of tests involving specimens having bolt diameters ranging from 12 to 16 mm and sheet thicknesses ranging from 1.5 to 3.0 mm, it has been found that the absence of out-of-plane constraint in untightened bolted connections leads to much lower bearing capacities than predicted by the specification's bearing strength equation. The effect is more pronounced for thinner sheets. An interesting finding is that the threaded bolt specimens had higher bearing capacities than the corresponding ones with shank bolts. It appears that the bolt threads provided some out-of-plane constraint to the connected sheet.

Sidelap and Structural Fastener Tests for Steel Deck Diaphragms, Yifei Shi, Shahab Torabian, Benjamin W. Schafer, W. Samuel Easterling and Matthew R. Eatherton

Steel deck diaphragm systems, which are commonly used for roof construction in steel-framed buildings, consist of many parts such as corrugated steel deck sheets, sidelap fasteners between adjacent sheets, structural fasteners from the sheets to the supporting beams or joists, chord elements, and collectors. Load-deformation behavior of a steel deck diaphragm system is typically dominated To understand and accurately model the behavior of steel deck diaphragm systems, it is therefore necessary to characterize the behavior of the individual fastenters. The effect of local geometry and detailing at these fasteners such as how the sheets fit together, fastener proximity to the sheet edge, and fastener location relative to the corrugation is not well understood

This paper presents a testing program including 80 specimens with single fasteners in flat steel deck sheets (not corrugated) that remove the effects of corrugation and edge distance. The testing program included two types of sidelap fasteners (#10 screws, #12 screws), four types of structural fasteners (powder actuated fasteners, pneumatic power actuated fasteners, arc seam welds, #12 screws), as well as other variations such as number of deck plies for structural fasteners (1 ply to support, 2 ply, and 4 ply), deck thickness (22 gage, 20 gage and 18 gage), and loading (monotonic and cyclic). A companion suite of 60 monotonic and cyclic tests were conducted with deck geometry and detailing representative of typical construction. By comparing results between these two sets of tests, the effect of deck geometry and fastener location was isolated.

Proposal to Improve the DSM Design of Cold-Formed Steel Angle Columns: Need, Background, Quality Assessment and Illustration, Pedro Borges Dinis and Dinar Camotim

This paper presents a proposal for the codification of an efficient design approach, based on the Direct Strength Method (DSM), for cold-formed steel equal-leg angle columns with short-to-intermediate lengths, i.e., those buckling in flexural-torsional modes. Initially, the available experimental failure load data, comprising fixed-ended and pin-ended ("cylindrical hinges") columns with several geometries (cross-section dimensions and lengths) and tested by various researchers, are collected and used to show that the currently codified DSM design provisions are not able to handle adequately short-to-intermediate angle columns and that a specific DSM-based design approach is needed to estimate the failure loads of such columns. Then, the paper presents a brief overview of the structural reasoning behind the DSM-based design approach proposed by Dinis & Camotim (2015, 2016). Next, the quality (accuracy and reliability) of the failure load estimates obtained with this design approach is assessed through the comparison with the above experimental failure load data and also a fairly large number of numerical failure loads. This merit assessment includes the determination of the LRFD resistance factors concerning the failure-to-predicted load ratios H́ it is shown that the value recommended, for compression members, by the North American Specification (AISI 2016), ♮ c=0.85, can also be adopted for short-to-intermediate angle columns designed with this DSM-based approach. Finally, the paper presents and discusses a few numerical examples, which illustrate the application of the proposed design approach and provide evidence of its advantages and benefits, when compared with the currently codified one.

Seismic behavior of cold-formed steel shear walls during full-scale building shake table tests, Wang, X., Hutchinson, T.C. and Hegemier, G.

Cold-formed steel sheathed shear walls are now emerging as a strategic vertical lateral load resisting component in seismic design. However, although a number of component cyclic test programs have been conducted in recent years to characterize their hysteretic behavior and guide design, system-level test programs to investigate their performance are so far lacking in the literature. To this end, a unique full-scale CFS-framed mid-rise building shake table test program was conducted to contribute to understanding the behavior of mid-rise cold-formed steel (CFS) wall-braced buildings under a multi-hazard scenario. The centerpiece of this project involved earthquake and live fire testing of a full-scale six-story CFS wall braced building constructed on the Large High Performance Outdoor Shake Table (LHPOST) at UCSD. This paper first provides a brief overview of the test program and summarizes the system-level (global) response of the test building during the shake table tests. Subsequently, a key focus of this paper is comparison of the component-level responses of various shear wall systems of the test building as well as their physical damage.

The 2017 AISI Cold-Formed Steel Design Manual, Joshua Buckholt and Helen Chen

The 2017 edition of AISI D100, the Cold-Formed Steel Design Manual (Manual) has been published. Updates to the Manual include: alignment with AISI S100-16, the North-American Specification for the Design of Cold-Formed Steel Structural Members (NA Specification); several new and varied design examples; additional discussions related to the design of cold-formed steel structures and components; and expanded bibliographies of relevant resources. The database of examples illustrating the Direct Strength Method (DSM) and new provisions in the NA Specification has been expanded. Also published with the Manual are the North-American Specification and its Commentary.

Bracing Design for Torsional Buckling of Cold-Formed Steel Wall Stud Columns, C.D. Moen

A method is presented for calculating the required brace stiffness and strength to limit torsional buckling deformation in cold-formed steel walll stud columns. The bracing (bridging) design method utilizes recent insight from classical stability solutions that define twist of singly and doubly-symmetric columns with an initial twist imperfection as a function of column compressive load. A wall stud design example is provided.

Finite Element Modeling and Validation of Steel Sheathed Cold-formed Steel Framed Shear Walls, Amanpreet Singh and Tara C. Hutchinson

The objective of this paper is to validate the concept of utilizing a truss-element based finite element model for capturing the in-plane cyclic response of steel sheathed cold-formed steel (CFS) framed shear wall. The model is developed within the OpenSees finite element platform. Steel sheathed CFS shear walls show shear buckling of their sheathing as a tension field develops. This inelastic behavior of the shear walls is replicated by using the Pinching4 material for truss elements acting along the tension field. Importantly, the model employs beam-column elements for framing members, rotational springs for representing frame stiffness and vertical springs for modelling hold-downs. The wall models were calibrated using experimental data available for 0.030-in. and 0.033-in. steel sheet sheathed shear walls with 2:1 and 4:1 aspect ratios and 6-in., 4-in. and 2-in. fastener spacing at panel edges. The specimens were subjected to symmetric reverse cyclic displacement-controlled loading using the CUREE protocol. Comparison amongst the experimental and numerical models demonstrate a high degree of accuracy in the estimated shear strength and hysteretic response of the shear walls and as such has the potential to be an important building block towards modeling full structural systems constructed of cold-formed steel framing.

Cold-Formed Steel Bolted Moment-Resisting Connections with Friction-Slip Mechanism for Seismic Areas, Marzie Shahini, Alireza Bagheri Sabbagh, Paul Davidson and Rasoul Mirghaderi

This paper presents investigation on cold-formed steel (CFS) beam-to-column moment-resisting (MR) bolted connections with high energy dissipation capacity suitable for seismic areas. Bolting friction-slip mechanism of the introduced CFS MR connection is developed as its main seismic energy dissipation fuse aiming to postpone or eliminate local buckling and yielding in the CFS MR connections. Finite Element (FE) modelling techniques are employed to effectively simulate the connections with an activated friction-slip mechanism. Hysteretic energy dissipation response of the connections with circular bolting (CB) arrangement designed to slip at 0.5Mp are presented. Based on the obtained FE results, full-scale physical tests on the CB connections have been performed under cyclic loading. Both the FE and the test CB connections comprised double back-to-back segmental-flange beams of 2, 4 and 6mm thicknesses. The results show that the bolting friction-slip mechanism developed for the CB connections can effectively delay local buckling and yielding in the CFS beams of as thin as 2 mm.

Distortional Buckling of Cold-Formed Steel Flanges Under Stress Gradient, Robert S. Glauz

The strength of cold-formed steel beams with stiffened flanges may be controlled by distortional buckling. Buckling stress prediction methods have been developed for flanges under uniform compression. However, channel sections are commonly used where bending occurs about the minor axis with flanges under stress gradient, such that the edges are in compression and the flanges may experience distortional buckling. Current design specifications do not explicitly address this failure mode, which could lead to unsafe designs. This paper presents and verifies an analytical approach for distortional buckling stress prediction for flanges under stress gradient. The approach is consistent with the design method used for flanges under uniform compression to facilitate straightforward incorporation into design specifications.

Planning the Future of North American Cold-Formed Steel Design Standards, Ben Schafer, Jay Larson and Helen Chen

Growth in cold-formed steel structures has long been tied to developing and advancing the engineering standards that govern their use in construction. The American Iron and Steel Institute (AISI) has taken a leadership role in this activity in North America since 1946. Conventional standards providing closed-formed solutions to member capacity, such as the recently completed suite of AISI Standards in 2015 and 2016. These standards have reached an impressive level of maturity given the complexity of designing entire (building) structural systems out of steel that is rarely greater than 2mm thick. However, the demands on the structural engineer designing cold-formed steel have evolved. System performance, resilience, and sustainability all present new challenges, while changing processes in construction and the integration of simulation tools in design alter engineering workflows and open up new opportunities. Cold-formed steel standards need to evolve to meet these demands and leverage new workflows. The Strategic Planning Committee of the AISI Standards Council facilitated a process that defined areas of focus (vision statements) for the AISI specification writing committees and then facilitated a process to generate prioritized issues for the subcommittees to address. Taken together the lists provide a snapshot of the needed work to evolve cold-formed steel standards, and in turn enable next-generation cold-formed steel structural systems. This paper provides a description of the strategic planning process and its significant outcomes, which will guide the efforts of AISI standards development over the next code development cycle and beyond.

Experimental and Analytical Studies of Cold-Formed Steel Sections with Edge-Stiffened Circular Holes Subjected to Web Crippling, Asraf Uzzaman, James B.P Lim, David Nash, A.M. Yousefi and Ben Young

Cold-formed steel sections are often used as wall studs or floor joists and such sections often include web holes for ease of installation of services. The holes are normally punched or bored and are unstiffened; when the holes are near to points of concentrated load, web crippling can be the critical design consideration. Recently, a new generation of cold-formed steel channel sections with edge-stiffened circular holes has been developed. The web holes are stiffened through a continuous edge stiffener/lip around the perimeter of the hole. In this paper, a combination of experimental investigations and non-linear finite element analyses are used to investigate the effect of such edge-stiffened holes under the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions; for comparison, sections without holes and with unstiffened holes are also be considered. A non-linear finite element models are described, and the results compared against the laboratory test results; a good agreement was obtained in terms of both strength and failure modes.

Parametric Studies and Design Recommendations of Cold-Formed Steel Sections with Edge-Stiffened Circular Holes Subjected to Web Crippling, Asraf Uzzaman, James B.P Lim, David Nash, A.M. Yousefi and Ben Young

A parametric study of cold-formed steel sections with edge-stiffened circular holes subjected to web crippling under one-flange loading condition was undertaken using finite element analysis. The effect of different hole sizes, edge-stiffener length and distances of the web holes to the near edge of the bearing plate on the web crippling strengths of channel sections were investigated. The web crippling strengths are influenced by various geometry parameters: the ratio of the hole depth to the flat portion of the web, a/h, the location of the hole as defined by the distance of the hole from the edge of the bearing divided by the flat portion of the web, x/h and the ratio of the edge-stiffener length to the flat portion of the web, q/h. In order to find the effect of a/h, x/h and q/h ratios on web crippling strength of channel sections with web holes, three separate parametric studies were carried out. The results indicate that with a suitable edge-stiffener length, the web crippling strength of cold-formed steel channel section with holes can be as high as the one without holes. In this paper, based on the finite element results a correlation are established for the web crippling strength of the channel sections without web holes, with unstiffened and edge-stiffened circular web holes corresponding with the ratios a/h, x/h and q/h for the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions, respectively.

Performance of Cold-Formed Steel Shear Walls wtih Frame Blocking and Double-Sheathing, Robert Rizk, Vincent Briere, Veronica Santos and Colin A. Rogers

This paper summarizes a laboratory based research program on blocked and double-sheathed cold-formed steel framed shear walls. The intent was to develop walls whose in-plane shear resistance exceeds that of configurations currently listed in the AISI S400 Standard. The results showed that the frame blocking can be used in the construction of walls whose resistance is at the limit of that found in AISI S400; however, the blocking will not adequately restrain the framing members if thicker sheathing is used. An approach was needed to minimize the effect of the eccentric loading caused by the sheathing and to account for the combination of axial compression and bending on the chord studs. Shear walls with steel sheathing placed on both sides of the framing demonstrated resistances up to twice those listed in AISI S400, without damage to the framing members, and similar ductility characteristics to previously tested CFS shear walls.

Influence of Gypsum Panels on the Response of Cold-Formed Steel Framed Strap-Braced Walls, Sophie Lu and Colin A. Rogers

In cold-formed steel construction the steel frame is supplemented with either diagonal strap braces or structural sheathing panels (typically steel or wood) to provide overall stability to the structural system and to directly transfer lateral wind and seismic loads through to the foundation as per the design provisions found in AISI S240 (2015) and AISI S400 (2015). Gypsum panels are often specified to provide a fire-resistance rating for the CFS frame, as well as to ensure that adequate sound-proofing exists between adjacent rooms or building units. The engineer may choose to rely on this gypsum to provide additional lateral resistance, as permitted in the AISI Standards. However, in the majority of cases the gypsum panels are considered to be non-structural elements of the building specified by the architect, and as such, are not taken into account in the design of the lateral load carrying system. Whether considered in the design process or not, these gypsum panels do augment the shear resistance of the lateral load carrying system. This study was carried out to evaluate the performance of combined strap-braced / gypsum-sheathed wall systems, with the intent of defining a corresponding design approach. Described herein are the findings of the laboratory phase of the project, comprising 35 wall specimens.

Experimental Investigation into the Behaviour of Back-to-Back Gapped Built-up Cold-Formed Steel Channel Sections under Compression, Krishanu Roy, Tina Chui Huon Ting, Hieng Ho Lau and James B.P. Lim

Back-to-back gapped built-up cold-formed steel channel-sections are used as compression members in cold-formed steel structures, such as trusses, space frames and portal frames etc. Because of the complex and non-uniform cross section of the back-to-back gapped built- up cold-formed steel channel columns, it is difficult to calculate the strength of these sections accurately. Current guidance by the direct strength method in the AISI Specification and the Australian/New Zealand Standard doesn't include the gap between the back-to-back channels, thus not being able to predict the axial capacities of these sections accurately. In the literature, very few results have been reported for such columns and specially investigated the effect of link-channel's spacing on axial strength of such columns. This issue is addressed herein. Forty new experimental results are reported, conducted on back-to-back gapped built-up cold-formed steel channel-sections, covering stub to slender columns. Axial capacity of the columns, load-axial shortening, load-axial strain, failure modes and deformed shapes were observed and reported in this paper. Also, the effect of link-channel's spacing on axial strength, is investigated. Test strengths are compared against the design strengths calculated in accordance with AISI and Australian/New Zealand standard for cold-formed steel structures. It is shown that the design standards can be conservative by as much as 53%, while predicting axial strength of such columns. Therefore, a modification to the non-dimensional slenderness, that considers the gap, is proposed which leads the design standards being within 5% conservative to the test results.

Human-Structure Interaction in Cold-Formed Steel Floor Systems: An Analytical Perspective, Sigong Zhang and Lei Xu

Designing cold-formed steel (CFS) floors to prevent annoying vibrations induced by human activities such as walking is still a challenge because human occupants not only generate impact loads but also behave as dynamical systems that interacting with structures. Such interaction, known as human-structure interaction (HSI), can be significant for lightweight floor systems particularly for the case when the mass of human occupants becomes comparable to those of the floors. The aim of this study was therefore to investigate the HSI in vibration of CFS floors subjected to human walking excitations by using the recently proposed damped plate-oscillator model to predict the dynamic responses of lightweight steel floor systems with occupants. Major novelties include considering the influence of stationary and moving occupants on HSI. In particular, three loading models were developed to predict floor responses induced by human walking: models of moving force (MF), moving damped oscillators (MDO), and moving and stationary damped-oscillators (MSDO). By using these models, comprehensive parametric studies on influences of walking step frequencies, mass ratios, damping ratios and walking paths to the dynamic responses of CFS floor vibration are presented.

New Proposals for the Direct Strength Method of Design of Cold-formed Steel Beams with Holes in Shear, Song Hong Pham, Cao Hung Pham, Colin A. Rogers and Gregory J Hancock

In the latest North American Specification for the design of cold-formed steel structural members AISI S100-16, an empirical approach is specified to design beams with web holes in shear. Recently, a Direct Strength Method (DSM) of design for shear for perforated beams with the aspect ratio (shear span / web depth) of 1.0 has been proposed. This paper presents a comprehensive review of the proposal and an experimental validation using a test series on beams with the aspect ratio of 2.0 and with various square and circular web opening sizes conducted at the University of Sydney, and other experimental data collected from the literature. As a result, it is proven that the earlier proposal reliably predicts the shear strength of perforated structures with centrally located square and circular web holes and with an aspect ratio up to 2.0.

A Finite Element Study of Corrugated Steel Deck Subjected to Concentrated Loads, Vitaliy V. Degtyarev
An extensive parametric study was initiated to get a better understanding of steel deck behavior under concentrated loads and to develop design recommendations for a wide range of deck profiles. This paper presents first results from the study related to 1.5-in. deep roof decks of types B and F. The study was performed on non-linear finite element models of deck validated against available test data. Deck gage, span length, span condition, concentrated load locations along and across the deck span were varied in the study. The observed deck behavior under concentrated loads, as well as the effects of the studied parameters on the effective distribution widths governed by the deck strength and stiffness, was presented and discussed. Design equations for predicting the effective distribution width for the studied deck profiles were presented.

Comparison of Experimental and Numerical Results for Flexural Capacity of Light-Gage Steel Roof Deck, Christopher H. Raebel and Dawid Gwozdz

The objective of this paper is to present a comparison between experimental results to each of two numerical analyses of cold formed steel roof deck in flexure. Prior numerical studies using the Direct Strength Method (DSM) and the Equivalent Width Method (EWM) have shown discrepancies between results obtained by the two methods. The goal of this research initiative was to compare results from each of the two numerical analysis methods to experimental results in an effort to determine which numerical method is most appropriate for analyzing steel deck in flexure.

Twenty-four physical tests were conducted using four different deck gages (22, 20, 18 and 16 gage) in both the deck's positive and negative positions. Detailed measurements of the physical geometry and the material properties of the deck samples were taken. Load was applied in a four-point bending scenario using a loading frame that engaged all flutes across the width of the deck sample.

Deck was loaded to failure. Applied load and several displacement measurements were recorded. Maximum load measurements and load-displacement plots were used to determine the maximum moment capacity in the deck.

Finite strip modeling using CUFSM v4.03 was conducted and analyses using the DSM and EWM are compared to experimental results. It was found that the DSM and EWM vary in their prediction of the nominal moment capacity across material grades and deck thicknesses, but tend to converge to a constant ratio at higher deck gages. The EWM was found to be more accurate for thinner gages and the DSM was found to be more accurate for thicker gages, but both methods provide reasonable results when determining steel roof deck capacities.

Low Fatigue Response of Crest-Fixed Cold-Formed Steel Drape Curved Roof Claddings, Krishanu Roy, James B.P. Lim, Amir Mohammad Yousefi, G Charles Clifton and Mahen Mahendran

Cold-formed steel roof claddings are subjected to significant suction/uplift pressures during high wind events. In New Zealand, the strong prevailing winds makes this a common occurrence. Suction pressures are generated by the turbulence of the wind flow around the building which can vary both spatially and temporally. The weakest link in the roofing system is the connection between roof sheeting and screw fasteners, which if fails, can lead to progressive collapse of the whole roofing assembly. Fluctuating high wind suction pressures can result in either static or fatigue pull-through failure of the roof sheeting at its screw fastener connections. Current literature has covered the static and fatigue wind uplift performance of crest-fixed corrugated and trapezoidal roof claddings. However, no research has been undertaken to understand the wind uplift performance of the typical crest-fixed cold-formed steel drape curved roof claddings used in New Zealand. This issue is addressed herein. In total, 35 large scale experimental tests are presented for crest-fixed drape curved steel roof claddings subjected to static and cyclic wind suction/uplift loads applied using a Pressure Loading Actuator. The material properties of claddings were determined using tensile coupon tests while the initial geometric imperfections of claddings were measured using a laser scanner. The critical fastener reactions were determined using a three axis load cell. Crack initiation, propagation of cracks, crack patterns and the number of load cycles to failure are discussed for such claddings under different load levels. Tests showed that the drape curved roof claddings are also subjected to localised dimpling and pull-through failures at their screw connections under static and cyclic wind uplift loads with the occurrence of low cycle fatigue failures under cyclic loading.

Computational Modeling of Joist-to-Ledger Connections in Cold-Formed Steel Diaphragms, Hernan Castaneda, Kara D. Peterman

Cold-formed steel framed buildings can involve a range of options for framing systems, including balloon framing, platform framing, and ledger framing. Transfer of lateral forces from the diaphragms to the wall system (and ultimately to the ground) depends on the interactions within the wall-diaphragm connection, which is dependent on choice of framing system. In ledger framing, floor joists are hung from top of wall studs via a rim track (ledger) and clip angle connection. Recent experimental efforts at Johns Hopkins University studied the wall-diaphragm connection with the goal of quantifying its contribution to overall diaphragm response. Results from these experiments showed the contribution to the rotational stiffness based on the location relative of floor joist and wall stud, location of clip angle, presence of top/bottom screws at ledger/joist flanges and presence of oriented strand board (OSB). In addition, it was observed that ledger flange buckling, and wall stud web crippling were the primary limit states. In current design codes there is not check for these limit states. The objective of this paper is to provide a robust computational model for a joist-to-ledger connection in CFS floor diaphragm with the ultimate goal of expanding the experimental test variables via a parametric study the computational model is compared and validated with experimental results. This detailed work at the connection level will motivate and inform future efforts for complete diaphragm system modeling. Furthermore, the work herein will lead to more robust modeling and prediction capabilities for CFS diaphragms.