Cold-Formed Steel Bolted Moment-Resisting Connections with Friction-Slip Mechanism for Seismic Areas

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Abstract

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 $0.5M_p$ 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.

Key Words: Cold-formed steel, Bolting friction-slip mechanism, Seismic energy dissipation, Moment-resisting connection.

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1. Introduction

A cold formed steel member is characterized by its light weight, high-strength low-alloy steels. The majority of CFS sections which are significantly thinner than hot-rolled counterparts, may experience different buckling modes [Trebilcock, P. J., 1994]. CFS moment resisting (MR) frames are being developed as a primary structural system. The seismic performance and the ultimate capacity of such structures rely on the stability of the individual CFS members such as beams and the connection response. If a premature local buckling failure of the connected beams is dominant, then the collapse of such structural system could be unavoidable, exhibiting a non-ductile response [Dubina et al, 2008]. Further, basic configurations of the CFS MR connections are unable to develop full moment capacity of the connected sections due to discontinuity of the load paths [Dao et al, 2013]. Therefore, to obtain an efficient CFS MR structural system the development of the system MR connections is a key step. In light of this, research is currently ongoing to improve the structural performance of the CFS MR connections [Sato et al, 2009&2010; Uang et al 2007&2010].

To increase local buckling resistance of CSF beams and to improve seismic performance of the CFS MR frames, a CFS MR connection has been recently developed using curved-flange sections and web-bolted through-plate connections [Bagheri Sabbagh et al, 2011]. Through extensive finite element analysis (FEA) and full-scale beam-to-column connection tests it was found that the developed connection significantly improves seismic energy dissipation and ductility capacity with CFS beam`s local buckling postponed after yielding initiated in the beam sections [Bagheri Sabbagh et al, 2012].

Amongst factors that can affect the CFS MR connections` response are the bolting configurations. In hot rolled steel frames slotted bolting has been designed to dissipate seismic energy through a friction-slip mechanism [Egor P. Popov et al,1994)]. To evaluate the effectiveness of the slotted bolting connection (SBC), an experimental study was performed by Shu et al.2016. The strength, stiffness and ductility performance of the SBCs have been compared with those of the regular bolted connections (RBC). The response of SBC characterized by friction, slip, bearing and shear actions of bolts resulted in an increase in the load carrying capacity at a larger displacement level. They also showed that SBC may reduce total seismic accelerations, increase ductility and provide better energy dissipation capacities Furthermore, large displacement level was resisted by bearing of the bolts against the sides of the slotted holes result in an increased strength hardening effect [Shu et al.2016].

The results presented in this paper are from an ongoing research project carried out at the University of Aberdeen to study the effects of slotted friction-slip bolting arrangements incorporated into the CFS MR connections. Through extensive FE simulations the proposed CFS MR connections have been developed investigating various types of CFS sections and connection configurations. The FE results have been informed full-scale connection tests carried out on the developed connections. Some selective results of the above research are presented herein as follows.

2. Design considerations

Figure 1 (a) shows schematic drawings of a CFS MR web-bolted through-plate (TP) connection comprising segmental-flange double back-to-back beam sections (Figure 1 (b)) and beam-to-TP connection using slotted circular bolting (CB) pattern (Figure 1 (c)). The segmental flange beam section has been chosen over the previously tested curved-flange sections due to its less manufacturing constraints during the forming process. Since the focus of this research is mainly on the beam-to-TP connection region the column has not been incorporated at this stage. The CFS beam sections have been assumed to be connected back-to-back at a distance of 500 mm required to prevent lateral-torsional buckling of each individual section along the length of the beam [AISC 341-10]. Nine bolts positioned at the center-to-center distance of 75 mm connect the beam webs to the TP passing inside the beam channels. The TP was designed to remain elastic following the capacity-based design approach. The choice of CB connection has been employed due to its more uniform bolt-group force distribution compared with the typical rectangular bolting patterns which is particularly important when designed for friction-slip mechanisms. To postpone local buckling in CFS beams, friction-slip mechanism within the beam-to-TP connection has been activated such that bolt slip triggers before local buckling initiates in the beams. FE simulations have been employed to determine the critical local buckling load which can then be incorporated into the friction-slip design of the bolts.

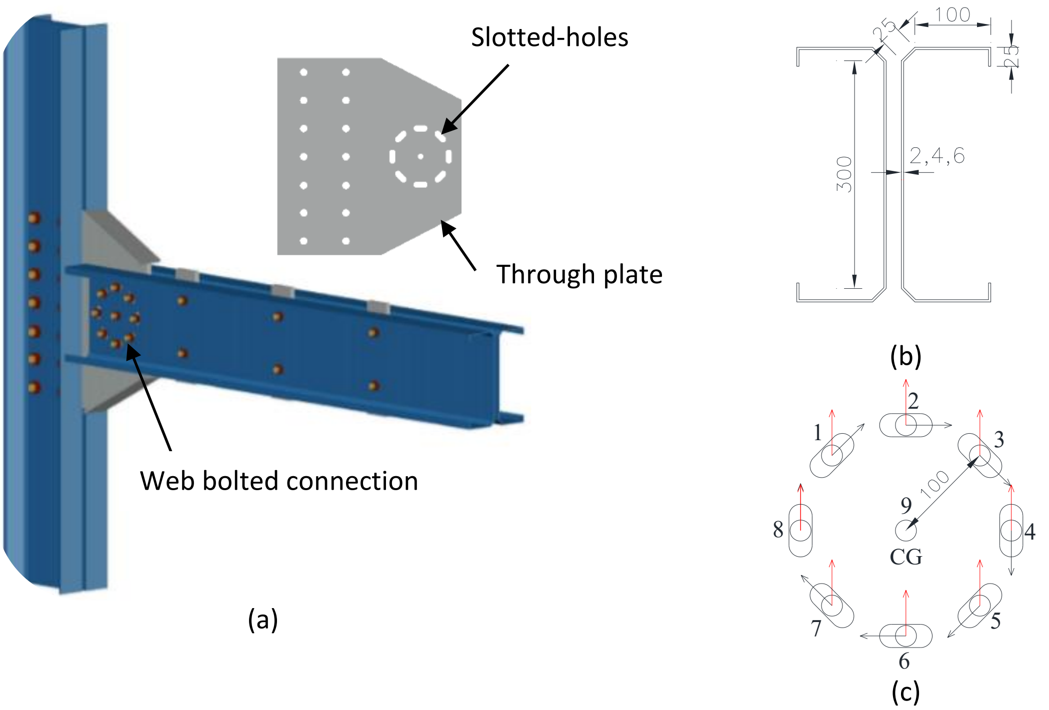


Figure 1. (a) CFS MR connection, **(b)** Segmental CFS beam cross sections and **(c)** CB bolting pattern.

3. FE Modelling specifications and methodology

The proposed CFS MR connections have been modelled using the FE package ABAQUS 6.14. Figure 2 shows a typical FE model of a 2.5 m length cantilever beam bolted to the TP representing a 4 m span MR frame subjected to lateral loading with mid-span inflection points. Nonlinear post-buckling analysis was performed using the methods available in ABAQUS which is suitable to predict instability and material and geometrical nonlinearity of a structure [ABAQUS 6.14]. As mentioned above columns have not been included in the FE models at this stage of study which focuses on the beam-to-TP connection. The connection between the TP and the column has therefore been modelled using rigidly supported nodes at the positions of the bolts as highlighted in Figure 2. To simulate the restraining effect of a concrete floor, the top flanges of the beams were laterally restrained (in the X direction). Tie constraints were employed to connect the beam sections through their webs distanced at 500 mm along the length of the beam. Vertical loading applied at the tip of the beam was uniformly distributed throughout the depth of the webs (shown by arrows in Y-direction) avoiding stress concentration effects. The S275 steel Grade has been used with yield strength (f_y) of 275 MPa, ultimate strength (f_u) of 485 MPa, modulus of elasticity (E) of 210GPa and Poission`s ratio of 0.33. A bi-linear stress-strain material curve has been adopted with the strain hardening ratio assumed to be 0.01. The friction-slip bolts have been modelled using fastener connections available in the ABAQUS library [ABAQUS 6.14].

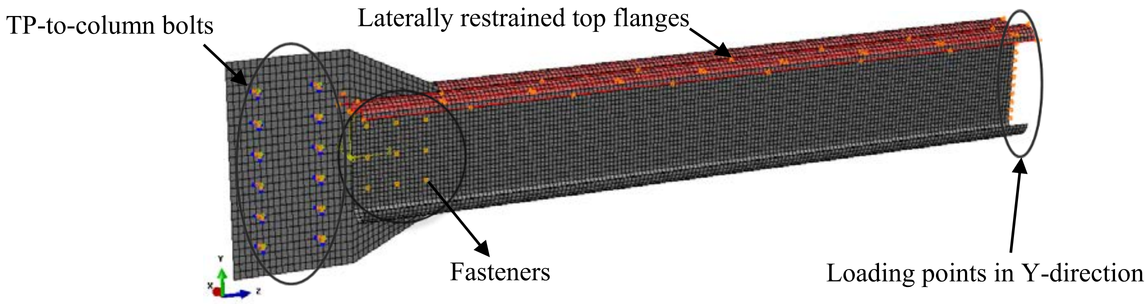


Figure 2. CFS MR beam-to-TP connection FE model

4. FE results on the CFS MR connections

To determine the seismic hysteretic response of the introduced CFS MR connections, cyclic loading protocol has been adopted from the AISC seismic provisions [REF]. This protocol is used for qualifying MR joints as special and intermediate moment frames. Through the above FE models (shown in Figure 2), the adopted loading cycles have been applied to the CB connections (illustrated in Figures 1 (a) and 1(c)) having 300 mm high S-section beams each with 2, 4 and 6 mm thicknesses (see Figure 1 (b)). Figure 3 shows the obtained hysteretic normalised moment (M/M_p)-rotation (θ) curves of the CB connections with bolt slip load activated at $0.5M_p$. Where M is the bending moment calculated at the centre of the beam-to-TP connection, M_p is the plastic bending moment of the beam sections for each of the thicknesses and θ is the beam-end rotation in radians. From these curves, one can observe all the CB connections have generated a highly stable hysteretic response which can dissipate seismic energy through bolting friction-slip mechanism without degradation up to a very large connection rotation. Activation of bolt slip at $0.5M_p$ successfully postponed local buckling/yielding far beyond the required rotation corresponding to the drift angle for the design earthquake-level [REF]. The reason being that the ductility demand is mainly provided through the bolting friction-slip mechanism and therefore, the beam sections have been successfully protected against local buckling. This FE observation has been further investigated through a programme of physical testing which are presented in the following section.

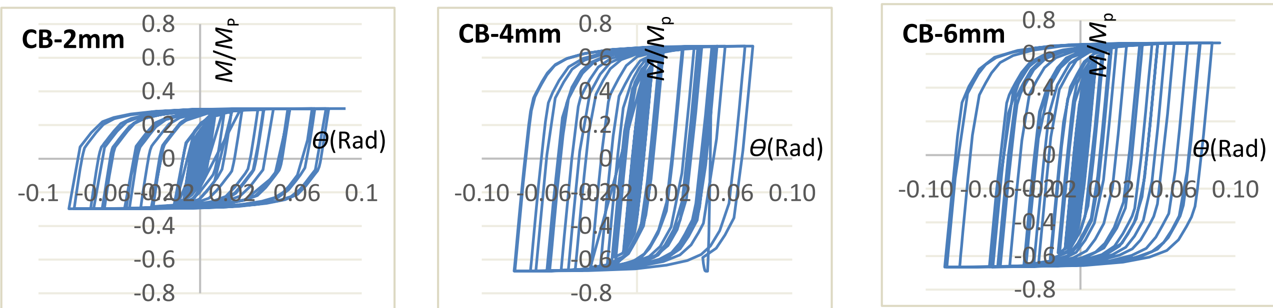


Figure 2. Hysteretic response of CB connections having 2, 4 and 6 mm thickness S-section beams, all with $0.5M_p$ bolt slip

5. Experimental study on the CFS MR connections

A set of full-scale physical tests has been conducted under cyclic loading on the CB connections developed through the FE modelling, as presented in the previous section, following the AISC Seismic Provisions [REF]. The testing CB connections have the same dimensions and configurations as those of the FE models with the S-section beams of 2, 4 and 6 mm thicknesses and the bolting friction-slip mechanism activated at $0.5M_p$.

5.1. Test set up

Figure 4 shows the test set-up comprising a vertically aligned 2.5 m S-beam connected to a strong double-channel hot-rolled steel stub-column which was laid down and bolted on a strong concrete floor. The slotted holes were placed on the TP (as shown in the zoom view in Figure 4) with the length of 10 mm obtained from the FE models as the maximum travelling distance of the bolts inside the holes under cyclic loading with the aim to avoid bearing action of the bolts against the connected plates. The test specimens were loaded through hydraulic actuators located at each side of the beam end with the load cells placed between the actuators and the beam to record the applied loads. Skidmore-Wilhelm equipment was used to tighten the bolts at the predicted slip level of $0.5M_p$. Two scenarios were considered when pre-tensioning the bolts: (i) initially with bolt pre-tensioning at the predicted slip; and then (ii) pre-tensioning at the maximum slip resistance. The former is to provide the connection ductility and energy dissipation capacity through the friction-slip fusing mechanism; while the latter scenario is to shift the demands into the beam section with expected local buckling and yielding failures.

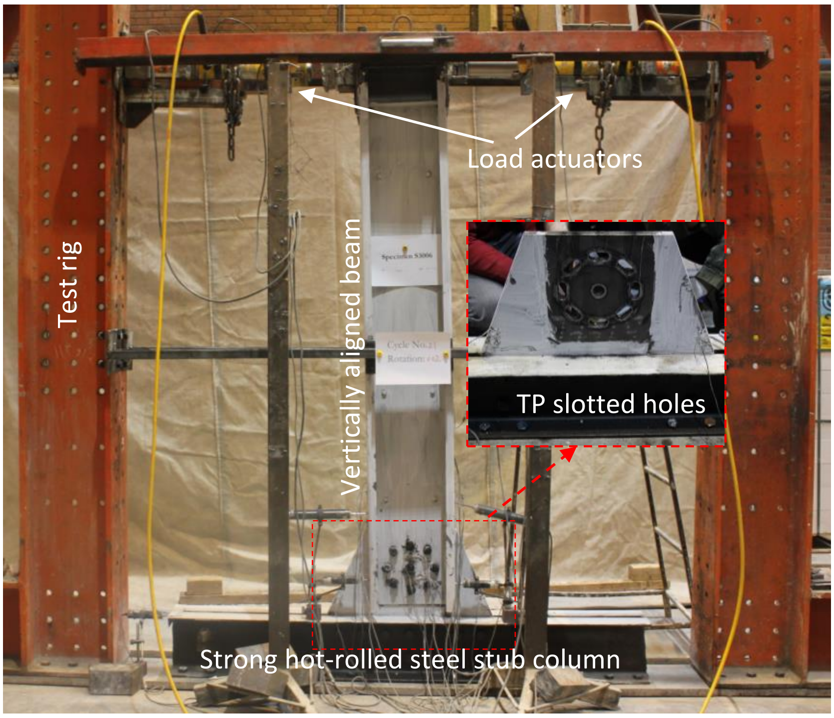


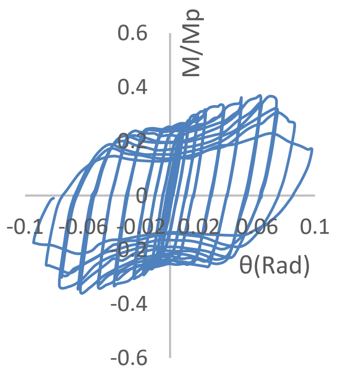
Figure 4. Test setup of the vertically aligned CB connection

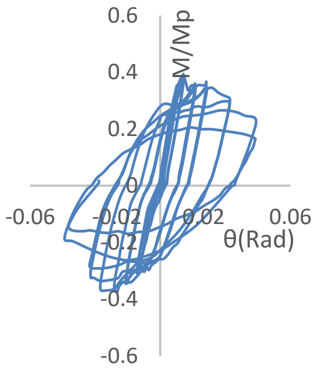
5.2. Test Results

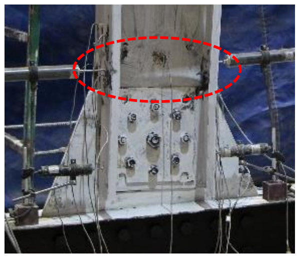
Presented in Table1 are the hysteretic curves and the corresponding CB connections at the maximum rotation obtained through the tests with activated friction-slip mechanism at $0.5M_p$ and slip-resistant connections referring to the above bolt pre-tensioning scenarios. As predicted by the FE results the hysteretic response of the CB connections are highly stable with local buckling eliminated for higher thickness beams (4 and 6 mm S-sections). In the connection with the 2-mm beam section, however, local buckling initiated at around 0.05 rad rotation which is still far beyond the corresponding 0.02 storey drift angles at the design-earthquake levels required by seismic codes [Eurocode 8]. Therefore, the bolting friction-slip was the main fusing mechanism resulted in the beam sections to remain largely elastic. On the other hand, the CB connections with slip-resistant bolting developed significant web buckling (shown by dashed ovals) led to strength degradation towards the last cycles. The CB connection with the 2-mm beam was the most affected connection by a premature local buckling which reveals the paramount importance of the bolting friction-slip mechanism for lower thickness CFS beams. In the connections with higher thickness 4 and 6 mm beams the nine-bolt arrangement was not sufficient to achieve a slip-resistant connection. Therefore, four additional bolts were added at the corners of the connections, though still a degree of slip was activated during the loading cycles.

Table 1- Hysteretic curves and CB connections at the maximum rotation

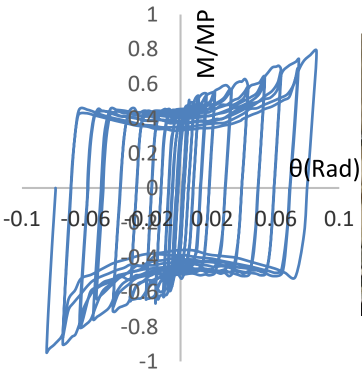
0.5M_p slip level	Slip-resistant

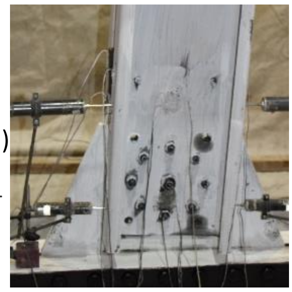


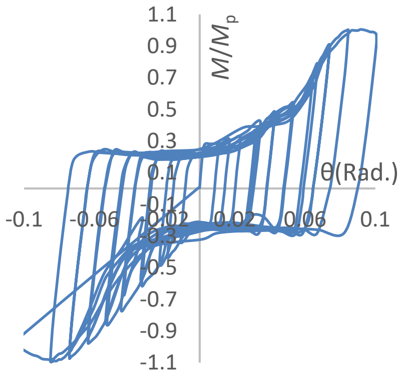


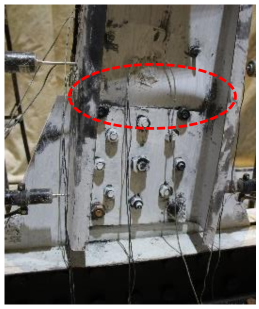


CB connection with 2mm S-beam

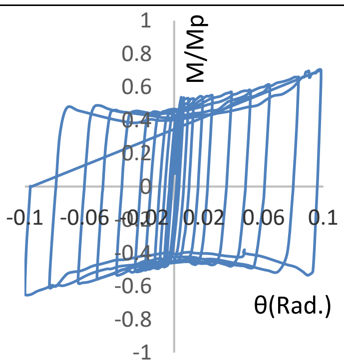


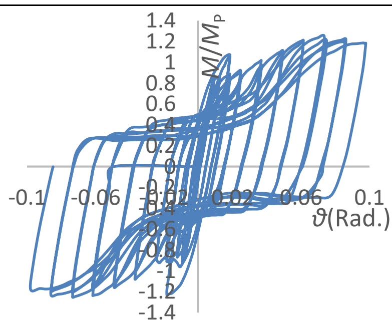


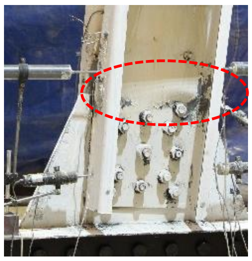




CB connection with 4mm S-beam







CB connection with 6mm S-beam

6. Conclusions

By means of FE modelling and physical tests the effect of bolting friction-slip mechanism has been investigated on CFS moment-resisting (MR) connections comprising segmental-section (S-section) beams and circular bolting (CB) arrangement. A 2.5 m long beam having 300 mm high section and 2, 4 and 6 mm thicknesses were used both in FE models and test specimens. The FE results show that activation of bolt slip at $0.5M_p$ prior to local buckling in CFS beams provide a highly stable hysteretic response reaching a very large rotation without strength degradation. The test results on the developed CB connections led to the similar conclusions as those of the FE results, with the exception of the connection with 2-mm beam thickness that underwent local buckling at 5% rotation after the initial slip. Overall, both the FE and test results revealed that bolting-friction fusing mechanism can effectively eliminate or postpone local buckling in CFS beams far beyond the limit of 0.02 storey drift angle required at the design earthquake-level. By increasing the bolts` pretension forces the ductility and energy dissipation demands were shifted into the beam sections with the consequence of local buckling and strength degradation in the hysteretic curves of the CB connections.

7. References

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