Cold-Formed Steel Moment-Resisting Connection: Numerical study

NORDIC STEEL 2024
The 15th Nordic Steel Construction Conference,
June 26–28, 2024, Luleå, Sweden

Cold-Formed Steel Moment-Resisting Connection:
Numerical study

Ward Alarab Safarani*, [a], Francesco Tondolo[a]

[a] Politecnico di Torino, Dept. of Structural, Geotechnical and Building Engineering, Italy
ward.safarani@polito.it, francesco.tondolo@polito.it

ABSTRACT

The contemporary demand for economically and environmentally efficient structures is crucial for establishing sustainable modern infrastructure. A prominent example of this can be seen in the most recent advancements, where the utilization of Cold-Formed Steel (CFS) framing systems has attracted considerable notice in the steel construction industry. This increased interest can be attributed to CFS advantages as a lightweight structural material. At present, CFS are used as primary structural elements. However, its application is still limited to low- and mid-rise buildings due to limited performance. Recent research has introduced an innovative CFS beam-to-column with through-plate connection, which has shown promising results in terms of both strength and ductility. This present research work investigates CFS bolted moment resistant connections numerically by using a finite element analysis (FEA) model validated against previously conducted analytical and experimental tests results. The aim of this study is to further contribute to the latest advancements in the field CFS construction trying to bridge the gap between research and industry by studying a connection model using a different beam cross-section shape that is folded flange beam section. The model is tested with three different configurations of stiffeners under cyclic loading conditions considering material non-linearity and geometrical imperfections. Moment-rotation curves and failure shapes are derived to discuss the cyclic behaviour of the connection with respect to the conventional connection configuration. The findings confirm that the performance of the connection with folded flange beam is in line with the connection employing the curved one and thus it can be a viable alternative to overcome limitations in practical applications.

Keywords: Cold-formed steel, CFS, beam-column connection, FE modelling, Cyclic behaviour

1 INTRODUCTION

Cold-formed steel (CFS) structural systems research has been gaining high attention over the last two decades driven by the environmental and economic efficiency of CFS members. However, their main structural applications are limited to structures of moderate height using CFS framing and portal frames systems. Hence, the development of lateral load-resisting systems suitable for high-rise buildings in seismic areas is still a brand-new topic, with a particular focus on CFS moment-resisting frame systems given their efficient seismic performance in terms of ductility and energy dissipation compared to conventional CFS braced-walls systems (1).

One of the most important contributions to the advancement of CFS moment resisting frame systems was an experimental study on an innovative beam-column with through plate connection (2). In this study, six bolted beam-to-column connections, employing through plates and curved flange beams with different configurations of out-of-plane stiffeners in the connection region, were tested to investigate the hysteretic behaviour of the CFS connections. The findings of this experimental activity indicated that CFS beam-column connections with curved flange beams can comply with standards for special moment frames. A following numerical study validated against the previous experimental work (3) has demonstrated that introducing more bends in the beam section flanges acting on the element level improves both the elastic and inelastic characteristics of the joint. Beams featuring an unlimited number of bends, especially with curved flanges, can delay local buckling and exhibit higher strength, stiffness, and ductility. Additionally, acting on the joint level, using out-of-plane stiffeners can improve significantly the seismic performance characterised by strength, ductility, and energy dissipation capacity.

Further numerical studies using finite element modelling on CFS beam-column with gusset plate connections under cyclic loading have been carried out taking into account geometrical imperfections, material properties and bolt slip (4). It was shown generally that the hysteretic behaviour of the tested specimen under cyclic loading and the moment-rotation response as well as failure modes could be predicted adequately by using the introduced cyclic FE models. Another similar study (5) has highlighted the impact of not only the bolting friction-slip mechanism on the cyclic behaviour of the connection but also the effect of beam profile shape and class, along with bolt arrangement providing more efficient solutions to facilitate the promotion of this type of joints.

The curved flange beam exhibits relatively good seismic performance, even though its manufacturing would be demanding, and its connection with the floor system could be challenging as well. Thus, an alternative folded flange beam has been presented as an alternative solution since it can overcome limitations related to manufacturing and construction, and also have very close performance to the curved one (5,6). Apart from the beam section shape, considerations that enhance the efficiency of the connection have been given by testing beam thickness, bolts arrangement, and gusset plate thickness. In a recent study (7), additional beam-column configurations engaging the flanges in the connection behaviour have been addressed considering the shape of the gusset plate, the connection type between beam and column whether the web or/and the flange are engaged as part of the joint and the thicknesses of both the beam and gusset plate. The latter aimed to research different configurations and evaluate their seismic behaviour and applicability. It was demonstrated that using beam-column connection with a rounded T-shape gusset plate with a thickness not less than twice the beam thickness provides the best solution among all web-connected connections maintaining a minimal restriction for floor system placing.

The key design parameters which influence the connection seismic response as have been illustrated in previous studies so far (1,3–7) are the following:

- material yielding and bearing around bolt holes.
- bolts distribution and bolt slippage.
- yielding lines resulting from buckling of the CFS cross-sectional plates.
- shape and dimensions of the beam cross section.
- stiffeners arrangements.
- beam thickness and gusset plate shape and thickness.

The previous connection configurations allow it to perform an adequate behaviour under seismic actions. However, they may not be suitable for real construction practice. Therefore, more experimental tests are needed to study these joints. Moreover, there is lack of standards and guidelines regarding CFS moment connections, thus their implementation at present is not ruled. There are many challenges that restrict the promotion of this kind of connection in industry. One is that the size of gusset plate needs to be reduced in a way that facilitates construction process. Additionally, the number of bolts is high and needs to be reduced. Furthermore, even though stiffeners have significant impact to the connection performance, still their installation process will cost and become more complicated for big projects where high number of connections is required.

The objective of this study is to investigate and assess numerically the performance of the CFS beam-column connection with gusset plate highlighting the key design parameters addressed in the previous studies with the consideration of the manufacturing and construction restrictions as well. Even though it was demonstrated by (5) that folded flange beam section can be a good alternative to curved flange beam section, the study was under monotonic loading and no numerical cyclic test has been performed to understand the behaviour of such connection with folded flange beam under cyclic loading. Therefore, a folded flange beam with chamfered shape gusset plate has been modelled taking into account material non-linearity and geometrical imperfections to compare it with beam-column connection with curved flange beam and chamfered gusset plate under cyclic loading conditions.

2 NUMERICAL MODEL

FE models of CFS bolted beam-to-column with through plate (gusset plate) connection have been created using FE Software ABAQUS (8) and validated against previous experimental and numerical tests (2–7,9). In *Fig. **1***, a 3D view of the connection model is presented.

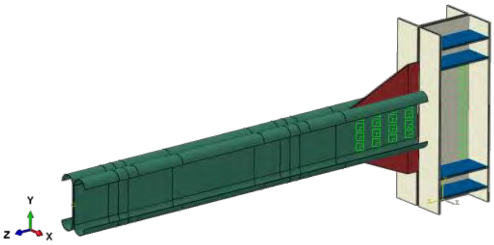


Fig. 1. General 3D view of the connection model

The numerical model validation against experimental test has been conducted with regard to the experimental test specimens A1, A2 and A3 (2). The beam cross-section used in these specimens are curved flange beam while the gusset plate is a typical T-shape chamfered plate. Advanced numerical models have been introduced in this study using folded flange beam with the typical gusset plate (Models F1, F2 & F3). The general models specifications considered in this study are illustrated in *Table 1*. The model includes 3 different configurations according to stiffeners arrangements as shown in *Table 2*. In total 6 models have been developed.

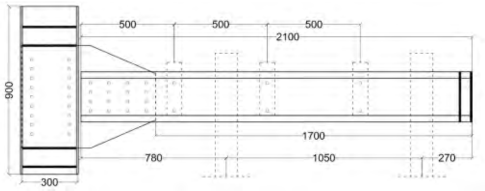
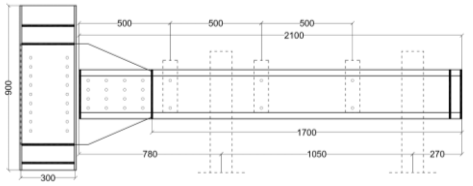
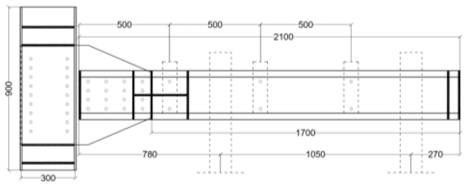
Table 1. General specifications of the numerical models

Models	Beam Section	Beam Thickness [mm]	Gusset Pl. Type	Gusset Pl. Thickness [mm]	Beam Stiffeners Thickness [mm]
A1, A2, A3	Curved	3	Chamfered	8	8
F1, F2, F3	Folded	3	Chamfered	8	8

The simulation of the connection in terms of geometry, material, and boundary conditions has been performed to be in correspondence with research experimental test (2) following suggested procedures given in recent numerical studies (3–7,9). Both monotonic and cyclic loading conditions have been considered. The main parameters that have to be incorporated into ABAQUS to obtain a coherent model and simulate the actual behaviour are the following:

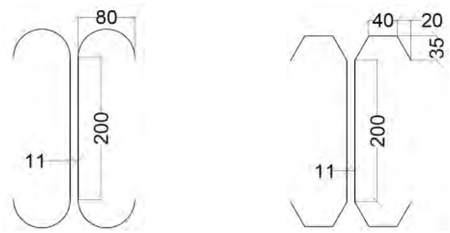
1. Geometry.
2. Material and Geometrical Imperfections.
3. Bolts.
4. Boundary conditions.
5. Loading type and conditions.
6. Mesh and Elements type.
7. Type of the analysis.

Table 2. CFS connection configuration detail considering different stiffeners arrangements.

Stiffeners configurations	Side view of beam-to-column connection specimens all dimensions in [mm]
1	
2	
3	

2.1 Geometry

Table 1 reports general specifications adopted for the models under study. Beam cross-section dimensions for all models are shown in *Fig. 2*. The details of curved flange beam section, reported in (2) are shown in *Fig. 2* (a). While the dimension of the folded flange section, reported in (5,6), is shown in *Fig. 2* (b).



(a) (b)

Fig. 2. Beam dimensions for (a) Curved flange beam and (b) Folded flange beam (present study).

The geometry of the gusset plate with the arrangement of bolts implemented in the connection configuration is reported in (2). Three different arrangements of stiffeners suggested by (3) have been included into the model for comparison purposes. The details of the connection configurations with all the arrangements of the stiffeners are illustrated in *Table 2*.

2.2 Material and Geometrical Imperfections

Nonlinear elastic-plastic stress-strain material model suggested by (10) is used to simulate the material behaviour of CFS beam and gusset plate (7). The results of coupon tests by (11) are used to fit the adopted material model. The stress-strain curves for the beam and gusset plates which were incorporated into ABAQUS (8) were constructed using the material properties for beam and gusset plate from coupon test given in *Table 3*.

Initial geometrical imperfections have been accounted for as well in the modelling process. Following the suggested procedure by (6,7), geometrical imperfections were introduced performing first buckling analysis to assess the buckling modes and then selecting the type of dominant buckling type based on first buckling mode resulted. The initial shape of the connection configuration is generated for the main model taking into account amplified initial deformation of the dominant buckling shape.

The combined hardening rule was adopted in ABAQUS model to simulate the hysteretic behaviour of the steel material.

Table 3. Material properties for beam and gusset plate from coupon test (11) - specimen A

Specimen	Beam A	Gusset A
$\sigma_{0.2}$ [MPa]	313	353
σ_u [MPa]	479	516
$\varepsilon_{0.2}$ [-]	0.00349	0.00368
E [MPa]	210000	210000
E_0 [MPa]	2100	2100

2.3 Bolts

The bolt behaviour under monotonic and cyclic loading was simulated by employing point-based fasteners with simplified connection element. This will lead to nearly accurate results considering lower computational time and effort compared to more complex solutions (6). The modelling technique of point-based fasteners needs to identify surface layers which are beam web -gusset plate surface-beam web for the beam bolt group and column web -gusset plate surface-column web for the column bolt group. It is worth mentioning that the bolt slippage has not been taken into consideration in this study and the numerical results validation has been performed with respect to specimens A where no slippage is detected during the test (7).

2.4 Boundary and Loading Conditions

The boundary conditions have been introduced to the model with respect to the reference experimental test conditions (2) and the subsequent validated FE models (5–7). Monotonic and cyclic loading have been imposed by applying a controlled displacement at the end of the beam with regard to the loading protocol introduced in (12).

2.5 Analysis and Elements Type

The type of analysis performed is general static analysis. The mesh size of 10 x 10 mm for all connection elements was selected with S4R general-purpose finite element which is a 4-node, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation. It has proven to accurately simulate the behaviour of thin-walled CFS members (7).

3 RESULTS AND MODEL VALIDATION

3.1 Numerical model validation

Numerical analysis has been performed on specimen A1, A2 and A3 to obtain the cyclic moment-rotation curves and compare them with the corresponding curves extracted from the experimental test and previous FE models (2,4). The comparison of moment-rotation curves between FE model created in this study and the experimental results reported in (2) is presented in *Fig. 3*. The moment-rotation curves were plotted considering the ratio of the bending moment to the plastic moment of the CFS beam denoted with M_p and the ratio of beam end displacement to the distance between the beam end and gusset plate. The present numerical model results demonstrate a good fitting with respect to the previous experimental test and they are in line with previous FE models results.

3.2 Numerical model results and discussion

This part entails the discussion of the results of the numerical model F which was modelled to incorporate an alternative beam cross-section which is folded flange beam section.

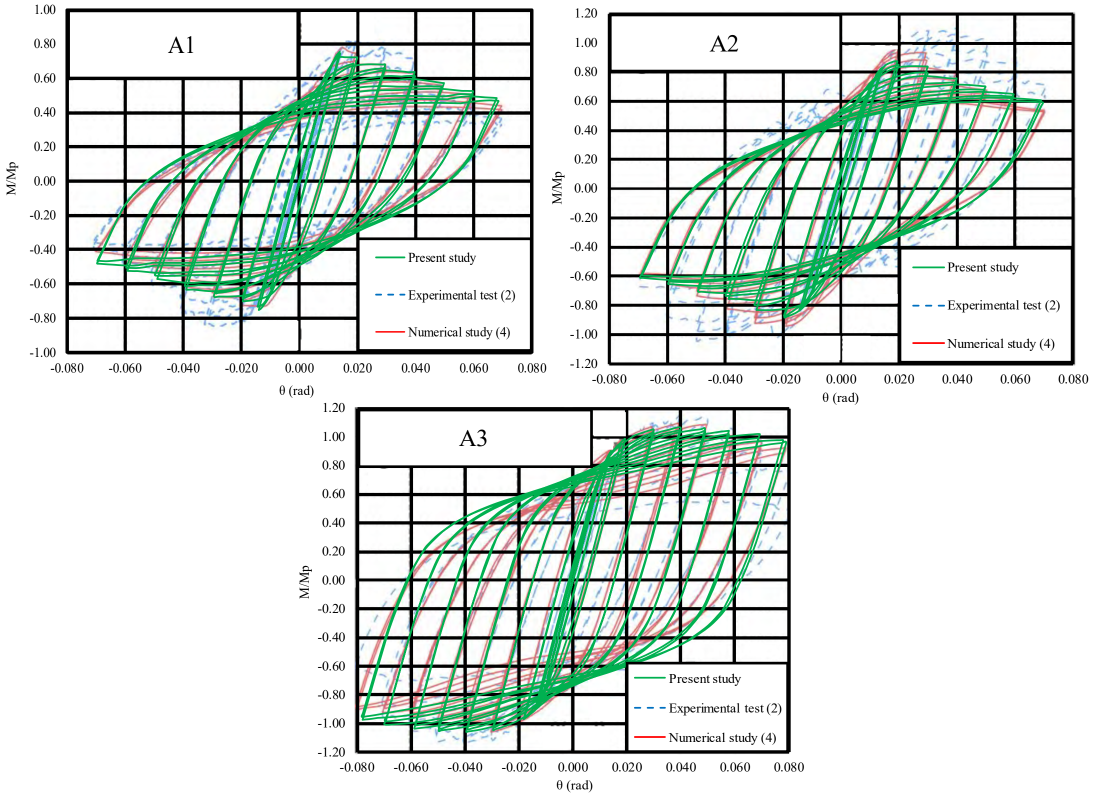


Fig. 3. M/Mp-θ curves of the experimental test by (2), *numerical test by* (4) *and present study*

The results are discussed comparing both the shape of failure mode and the obtained moment-rotation curves respectively. Failure shapes resulted from cyclic loading application to the connection models are shown in *Fig. 4*. Generally, it can be demonstrated that F models exhibit similar behaviour to A models. Failures in models A1, A2, F1, and F2 occur in the beam web at the edge of the gusset plate, whereas in models A3 and F3, buckling is delayed and takes place in the beam flanges outside the connection zone.

The moment-rotation graphs outlined in *Fig. 5* for the obtained FE models illustrate a good similarity between the behaviour of the connection using a folded flange beam and the one employing a curved flange beam. It can be observed that the strength capacity of the connection for F models is similar or even higher than models simulating A type specimen. This can be highlighted as well in *Fig. 7* which summarize the moment rotation values at the characteristic points of the obtained cyclic curves. The characteristic points, which represent yielding, maximum capacity, ultimate strength, and failure, are determined by outlining the envelope of the cyclic curve for each model, as shown in the example for model A1 in *Fig. 6*.

In model F1, F3 the strength degradation due to cyclic action is slightly lower than model A1, A3 respectively. As shown in *Fig. 5* and *Fig. 7* the connection model F3 achieved the plastic moment capacity, whereas for models F1 and F2, the moment capacity was 10-20% lower than the plastic moment capacity. This is due to the inclusion of stiffeners which substantially enhances the capacity of the connection and delays local buckling. However, this design choice presents challenges from a construction perspective due to increased complexity.

According to *Fig. 7*, models F1 and F2 experienced peaks that were 4% and 6% higher, respectively, compared to models A1 and A2, while for model F3, the peak capacity was about 2% lower than that of model A3. The ultimate rotation values for F1, F2, and F3 models, corresponding to 80% of the maximum plastic moment, indicate that the performance of the connection aligns with the requirements for special moment frames in (12).

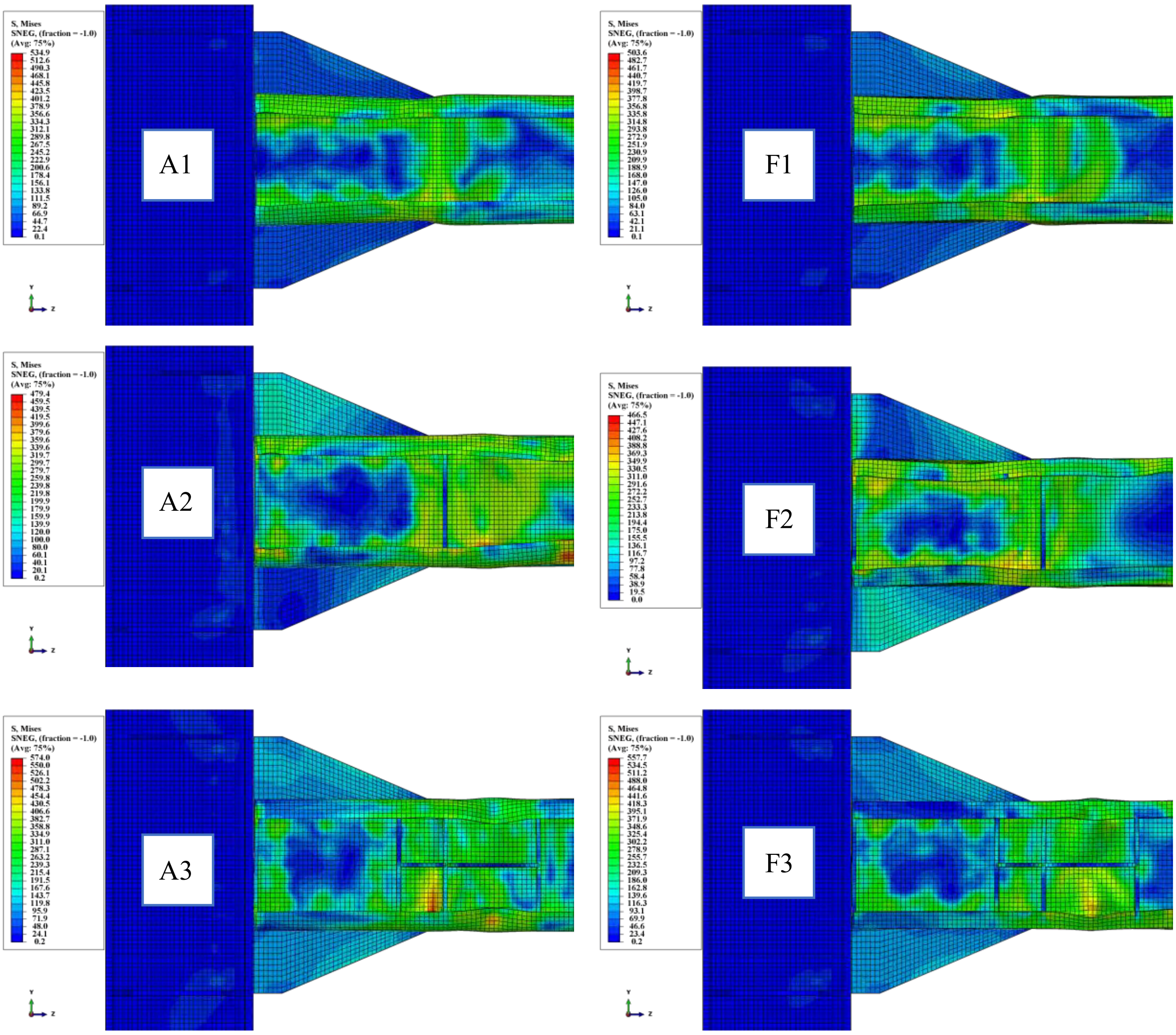


Fig. 4. Failure modes for A and F models (present study)

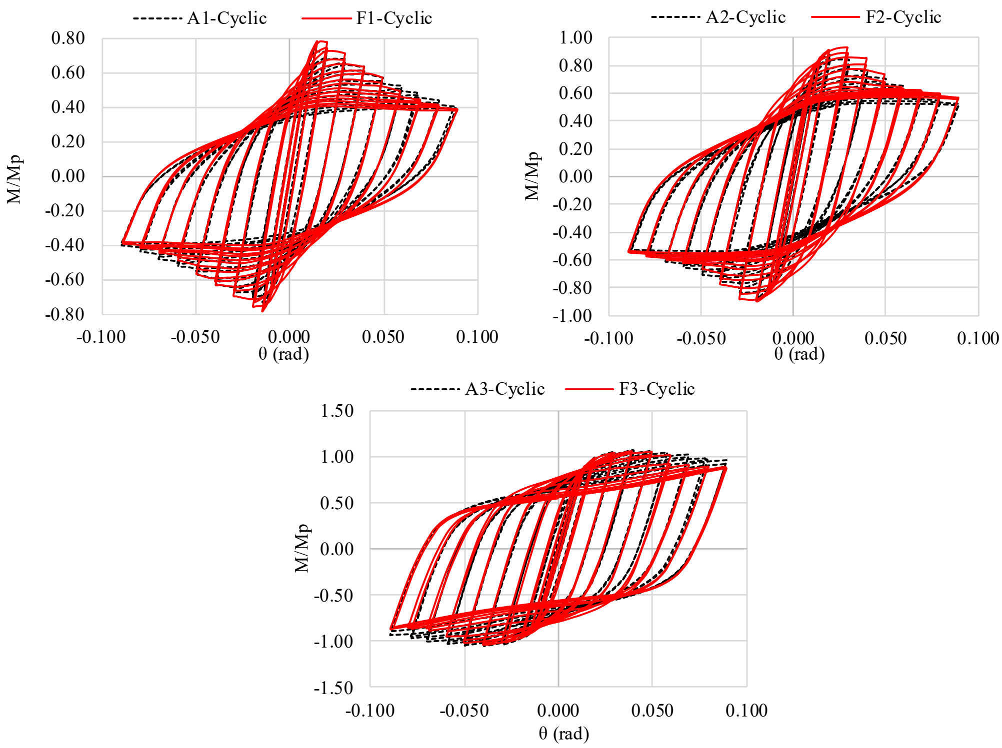


Fig. 5. Moment-Rotation curves for FE numerical models

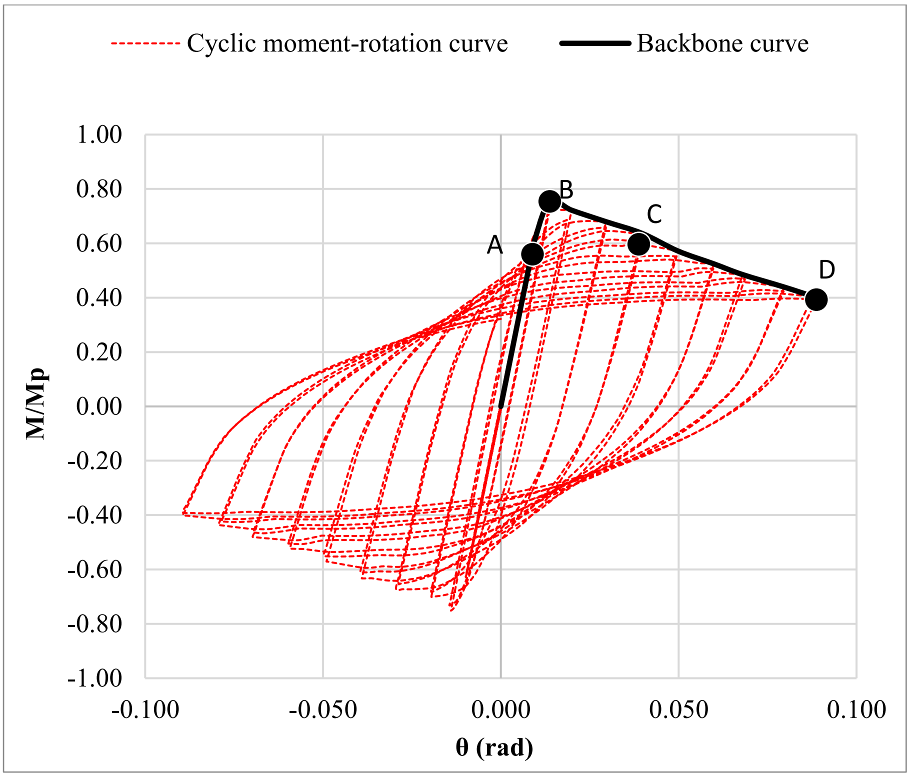


Fig. 6. Cyclic curve characteristic points for model A1

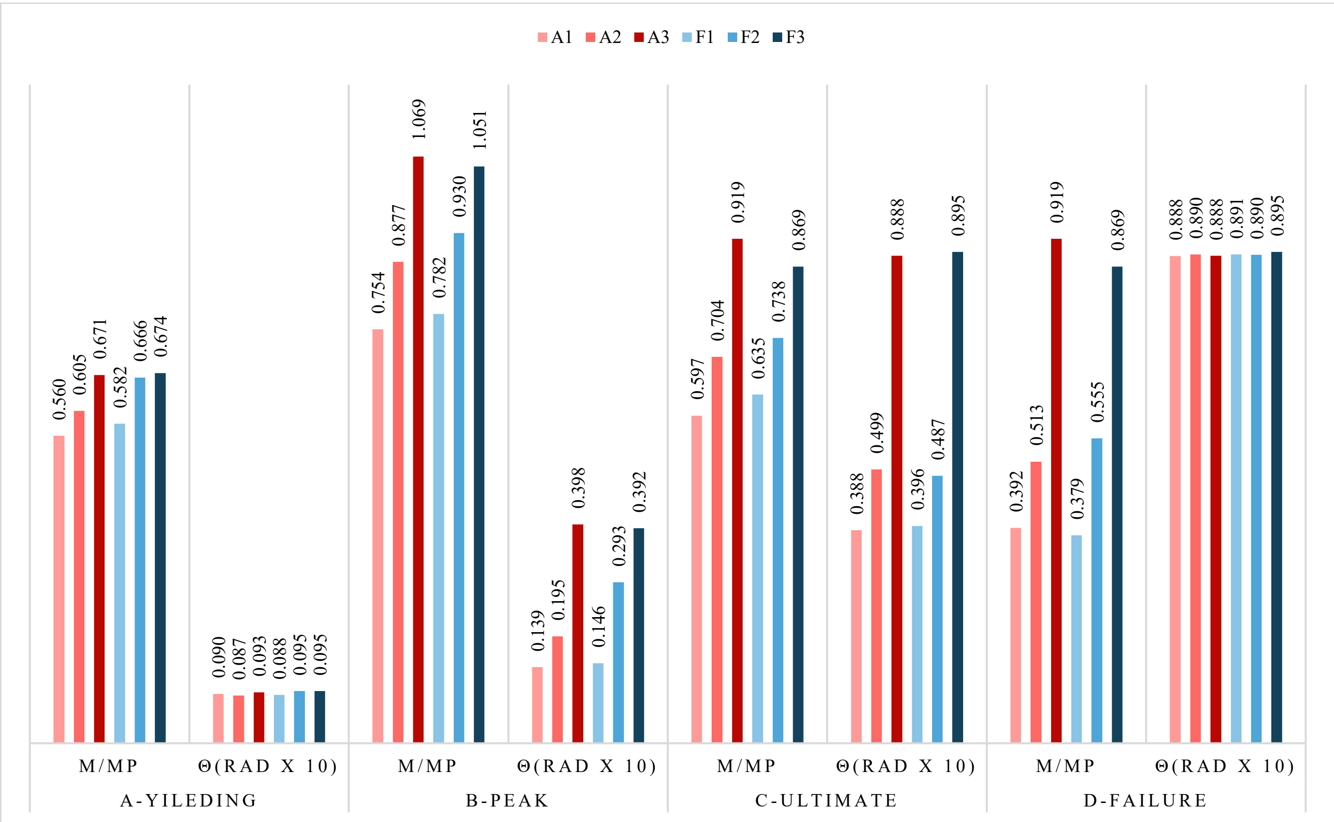


Fig. 7. Summary of the characteristic values for cyclic curves

4 CONCLUSIONS

A numerical study of Cold-Formed Steel (CFS) bolted moment-resisting connection has been carried out, specifically exploring the use of a folded flange beam under cyclic loading as an alternative to the curved flange beam introduced in (2) in order to address limitations in practical construction scenarios. The study employed finite element analysis (FEA) models, validated against both analytical and experimental tests considering material non-linearity and geometrical imperfections as well. The findings highlighted the potential of the innovative CFS beam-to-column connection with a folded flange beam under cyclic conditions, showcasing promising results in terms of strength. The performance of this connection was compared to the introduced connection using a curved flange beam. In addition to that, three different connection configurations including stiffeners to enhance connection performance have been considered addressing the effect of stiffeners on the capacity of the connection and its implementation in real-world construction practices. The analysis outputs have been illustrated through moment-rotation curves and failure mode shapes.

REFERENCES

1. *A critical review of cold-formed steel seismic resistant systems: Recent developments, challenges and future directions.* **Hasanali, Maryam, et al.** s.l. : Elsevier, 11 2022, Thin-Walled Structures, Vol. 180, p. 109953. 0263-8231.

2. *Experimental work on cold-formed steel elements for earthquake resilient moment frame buildings.* **Bagheri Sabbagh, Alireza, et al.** s.l. : Elsevier, 9 2012, Engineering Structures, Vol. 42, pp. 371-386. 01410296.

3. *Development of cold-formed steel elements for earthquake resistant moment frame buildings.* **Bagheri Sabbagh, Alireza, et al.** s.l. : Elsevier, 4 2012, Thin-Walled Structures, Vol. 53, pp. 99-108. 02638231.

4. *Cyclic behaviour of bolted cold-formed steel moment connections: FE modelling including slip.* **Bagheri Sabbagh, Alireza, et al.** s.l. : Elsevier, 1 2013, Journal of Constructional Steel Research, Vol. 80, pp. 100-108. 0143974X.

5. *Seismic performance of cold-formed steel bolted moment connections with bolting friction-slip mechanism.* **Ye, Jun, Mojtabaei, Seyed Mohammad and Hajirasouliha, Iman.** s.l. : Elsevier, 5 2019, Journal of Constructional Steel Research, Vol. 156, pp. 122-136. 0143974X.

6. *Efficient design of cold-formed steel bolted-moment connections for earthquake resistant frames.* **Ye, Jun, et al.** s.l. : Elsevier, 5 2020, Thin-Walled Structures, Vol. 150, p. 105926. 02638231.

7. *Cold-formed steel beam-to-column bolted connections for seismic applications.* **Papargyriou, Ioannis, et al.** s.l. : Elsevier, 3 2022, Thin-Walled Structures, Vol. 172, p. 108876. 02638231.

8. **Dassault Systèmes Simulia.** *Abaqus 6.14 CAE user guide.* s.l. : Dassault Systèmes Simulia Corp, 2014.

9. *Ductile moment-resisting frames using cold-formed steel sections: An analytical investigation.* **Bagheri Sabbagh, Alireza, et al.** 4, s.l. : Elsevier, 4 2011, Journal of Constructional Steel Research, Vol. 67, pp. 634-646. 0143-974X.

10. *Finite element modelling of cold-formed steel beams under local buckling or combined local/distortional buckling.* **Haidarali, Mohammad Reza and Nethercot, David A.** 12, s.l. : Elsevier, 12 2011, Thin-Walled Structures, Vol. 49, pp. 1554-1562. 0263-8231.

11. *COLD-FORMED STEEL ELEMENTS FOR EARTHQUAKE RESISTANT MOMENT FRAME BUILDINGS (PhD Thesis).* **Sabbagh, Alireza Bagheri.** 2011.

12. **ANSI/AISC 341-16.** *Seismic Provisions for Structural Steel Buildings.* s.l. : American Institute of Steel Construction, 2016.