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BEHAVIOUR OF STEEL 2D MOMENT RESISTING FRAMES EQUIPPED WITH INNOVATIVE FRICTION CONNECTIONS UNDER SEISMIC AND COLUMN LOSS SCENARIOS

Roberto Carlevaris

Department of Structures for Engineering and Architecture (DIST)
University of Naples - Federico II
Via Forno Vecchio 36, 80134 Naples, Italy
roberto.carlevaris@unina.it

Abstract

Structures are not typically designed to withstand column loss. Therefore, finite element (FE) analyses are conducted on 1-storey 2D moment-resisting steel frame equipped with innovative friction connections, subjected to both seismic and column loss scenarios. Two identical frames are compared: the first frame is equipped with the original friction connections, while the second features modified friction connections with components designed for improved performance. Such modifications consist in stiffeners and two additional bolt rows on the T-stub flange and in shorter slotted holes on the haunch.
The two frames are compared by means of their bending moment-rotation curves, and the distribution of stresses and plasticization is analysed for further insights.
It is found that the original frame shows an excellent seismic response, but it fails prematurely when subject to column loss scenario. The modified connection shows a similar monotonic behaviour, but it is able to reach larger rotations in case of column removal.

Keywords: friction connections, Low Damage, column loss, moment-resisting steel frame, FE modelling

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1 INTRODUCTION

Steel has consistently demonstrated its effectiveness and reliability in seismic-resistant structures [1-6]. Modern building codes require structures to withstand a specific level of seismic activity while sustaining controlled damage. Their response should follow a predictable progression up to failure, ensuring a global collapse mechanism that maximizes energy dissipation. Advances in structural engineering and technology have improved the control, design, and prediction of building behavior, providing engineers with a range of structural solutions [6-15].

Since seismic actions cannot be directly controlled, the Low-Damage Philosophy focuses on minimizing structural damage caused by these forces. A key approach is to localize damage in designated structural components that can be easily replaced, thereby reducing repair costs.

One innovative solution in this field is the use of "friction connections" [16] which dissipate seismic energy through the friction between their components. New Zealand has been at the forefront of research in this area, with significant contributions from Clifton, MacRae, Khoo, Ramhormozian, and Chanchi Golondrino [17-25]. Their studies explored various materials, including mild steel, aluminum, brass, and abrasion-resistant steel, as well as various structural schemes as moment-resisting frames and braces. These devices primarily utilize Asymmetric Friction Connections (AFC), where the bolts are subjected to a composite action of axial load, shear and bending. European researchers, however, have adopted Symmetric Friction Connections (SFC) instead, to achieve a more predictable behaviour, avoiding bolt bending [26-27]. This effort has resulted in several European projects such as FREEDAM, FREEDAM+ [28], and the ongoing DREAMERS project. Thanks to these initiatives, these types of joints have been prequalified for seismic applications.

The FREEDAM joint resembles a Double-Tee connection, and it is designed for installation at the ends of beams in moment-resisting steel frames. A T-stub is positioned at the beam top flange, while a "friction device" – comprising two L-stubs, two friction pads, and a haunch – is placed under the beam bottom flange. These elements are clamped together using SFC bolts. The L-stubs are bolted to the column flange, while the haunch includes an upper plate that connects to the lower flange of the beam.

FREEDAM joints are designed as fully rigid and partial strength according to EN 1993-1-8 [29], meaning their design bending moment resistance is lower than the plastic bending resistance of the connected beam. The ratio of these two values is named utilization ratio of the connection. The bending moment resistance of these joints is directly influenced by the preload force applied to the damper bolts, as described by the equation:

$$M_{j,Rd} = \mu \, F_{pd} \, n_b \, n_s \, h_s \tag{1}$$

Where the friction coefficient of the friction shims μ, the preload on the SFC bolts F_{pd}, the number of SFC bolts n_b, the number of shear surfaces n_s, and the lever arm of the connection h_s are multiplied together.

The utilization ratio m is given by the ratio between the design bending resistance of the connection and the plastic resistance of the connected beam.

$$m = M_{j,Rd}/M_{pl,beam} \tag{2}$$

Although being seismically prequalified, their design procedure of the Original FREEDAM connection (J-O) does not directly account for Column Loss scenario. Previous studies [30] suggests that the T-stub connection could undergo brittle failure under column loss scenario, but no advanced study has been conducted on a complete frame subjected to such scenario. Additionally, the slotted holes on the haunch may undergo significant plastic deformation due to the bearing forces of the SFC bolts. To address these concerns, a reinforced FREEDAM connection (J-R) is proposed. The only difference between the J-O and the J-R joints resides in the T-stub and haunch component, depicted in *Figure 1* and *2*. The reinforced T-stub is designed to resist to the tensile action derived by the development of the catenary effect under column loss scenario, estimated as 0.4 times the axial plastic resistance of the connected beam. This reinforced T-stub has two additional bolt rows on the flange and stiffeners. The reinforced haunch is designed to accommodate a joint rotation of maximum 0.04 rad and has shorter slotted holes.

FE analyses of a 1-storey frame equipped with solution J-O and solution J-R are conducted and compared.

This study aims to investigate:

1. The behaviour of a 2D moment-resisting steel frame equipped with FREEDAM connections under monotonic seismic loading and column loss scenario
2. The effectiveness of the modified components (T-stub and haunch)

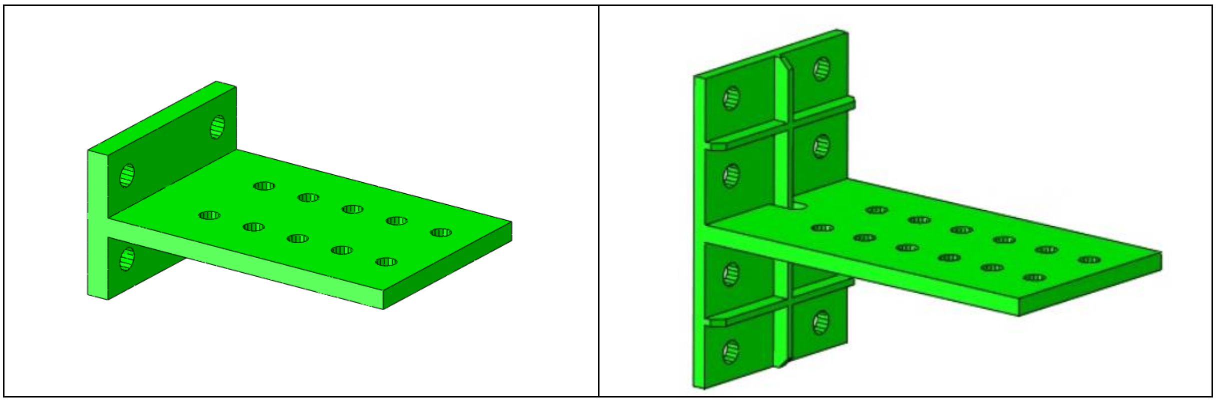

Figure 1: T-stub component, for the J-O joint (on the left) and for the J-R joint (on the right)

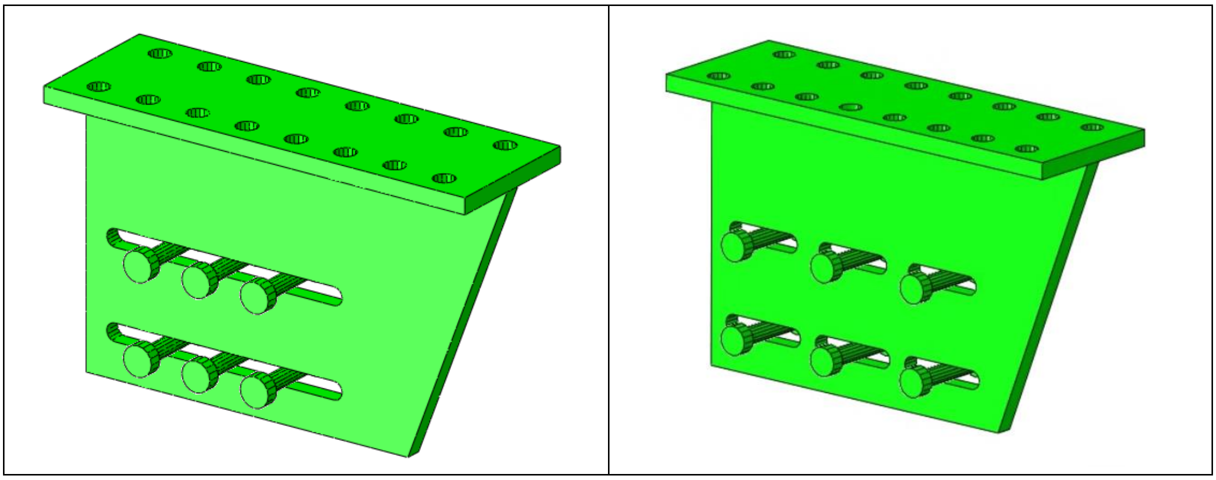

Figure 2: Hauch component with SFC bolts, for the J-O joint (on the left) and for the J-R joint (on the right)

2 METHODOLOGY

FREEDAM design procedure allows the structure to be designed according to action coming from a global structural analysis. This situation is common when the design is governed by serviceability checks on the interstorey displacements. A frame compliant with EN 1993-1-1 is hereby designed. The same frame is equipped with the Original FREEDAM device (J-O) in one case and the Reinforced FREEDAM device (J-R) in another. The joint assembly was extracted from a reference moment-resisting frame subjected to a seismic bending moment distribution.

Beam Profile	Column Profile	Span length [m]	Interstorey height [m]	Design bending moment [kNm]	Bending ratio [-]
IPE 750x147	HE 500 M	6.00	3.50	634.90	0.35

Table 1: Details of the frame.

Two loading scenarios *(Figure 3)* are investigated:

- In the *Monotonic Seismic Loading*, the column bases are pinned while the column tops are forced to move to the right. Imposed displacement increases monotonically.
- In the *Column Loss Scenario*, the sudden removal of the left column is modelled. The left column is equipped with vertical rollers and is forced to move downward. The right column is pinned at the base and has a vertical roller at its top. Imposed displacement increases monotonically.

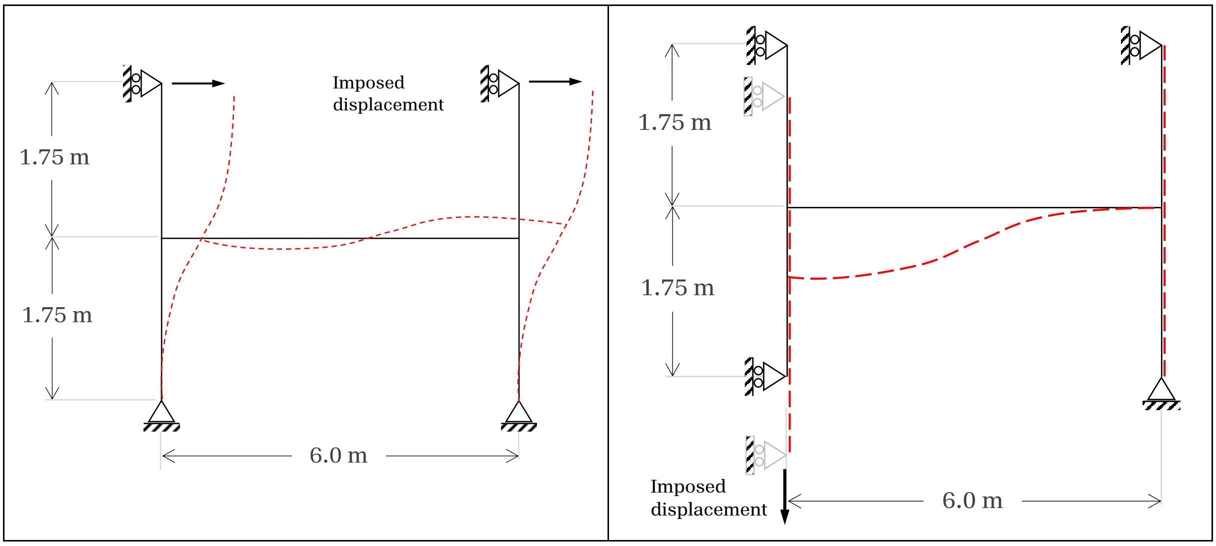

Figure 3: Boundary conditions for the Monotonic Seismic Loading (left) and Column Loss Scenario (right)

Figure 4: Front view of frame

3 FE MODELLING

The numerical analysis of the joint assembly was conducted using the general-purpose finite element (FE) software ABAQUS/CAE, version 6.14. The Dynamic Implicit Quasi-static procedure available in the ABAQUS library was employed, accounting for both geometric and material nonlinearities to ensure an accurate representation of the structural behaviour. All components are made of S355 steel, modelled with true stress-true strain curves derived from experimental coupon tests, while the bolts are Grade 10.9. The entire FE model uses 3D 8-node solid elements with reduced integration (C3D8R). A detailed sensitivity analysis was performed to determine the most suitable mesh size: a 5 mm mesh was adopted for the bolts, a 15 mm mesh for the joint components, and a coarser mesh for the remaining parts of the assembly to optimize computational efficiency while maintaining accuracy.

4 RESULTS

4.1 Monotonic Seismic Loading

The flexural response of the FREEDAM joint can be summarized in three main phases depending on the magnitude of the chord rotation:

- *Phase 1*, small rotations: the connection is in elastic range and the behaviour is linear, sliding of the SFC components is not activated
- *Phase 2,* medium rotations: the sliding in the SFC is activated, the bending moment-rotation curve of the joint exhibits a constant value equal to the design bending moment resistance. This is the ideal operational situation of the device.
- *Phase 3*, large rotations: sliding is prevented by the contact between the SFC bolts and the slotted hole edges. In absence of sliding parts, the device does not dissipate energy through friction, and the forces are transmitted through bearing.

The bending resistance of the FREEDAM connection (J-O) is similar under hogging and sagging moment. Analyses *(Figure 5)* show that when the connection is subjected to hogging bending moment the resistance is slightly higher with respect to the sagging bending moment case due to the lower tensile stiffness of the L-stubs with respect the T-stub [31]. The difference between the flexural response of the J-R joints and the J-O joints' one is negligible for small and small-to-medium rotations. For larger rotations the J-R joint exhibits a shorter *Phase 2*, reaching *Phase 3* hardening branch sooner. As stated before, the rotation under which the hardening branch is initiated can be designed by shortening or elongating the slotted holes on the haunch. This results in a pinched hysteresis loop for smaller rotations that can be beneficial for the control of the residual displacements after an earthquake [32]. The two curves show the same slope for the *Phase 3*. *Figures 6* shows the Von Mises stress distribution for the joint subjected to sagging bending moment, while *Figure 7* shows the PEEQ distribution on the haunch and SFC bolts. The haunch detailed with individual slotted holes (one for each SFC bolt) guarantees a beneficial strain distribution, with several points of contact between the bolts and the haunch. Conversely, the haunch where three SFC holes share the same elongated slotted holes suffers from strain concentration, resulting in premature bolt or haunch failure.

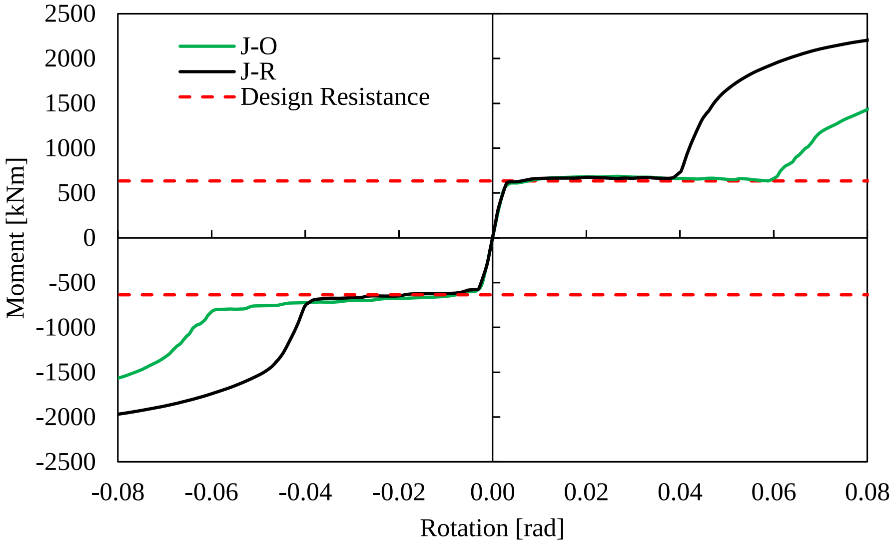

Figure 5: Bending moment over chord rotation curves for the joints. Sagging Moment has a positive sign.

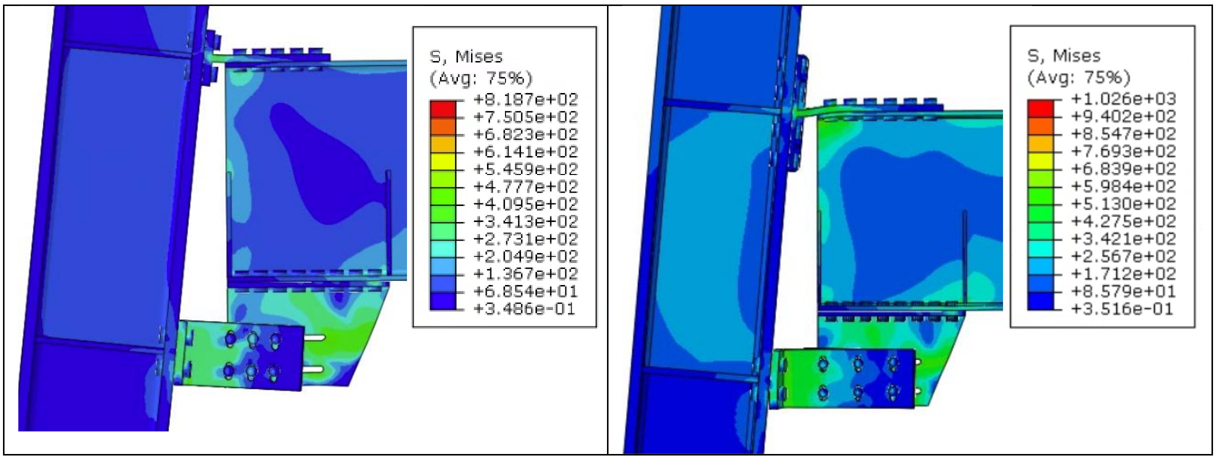

Figure 6: Von Mises stress distribution for the J-O joint (left) and for the J-R joint (right)

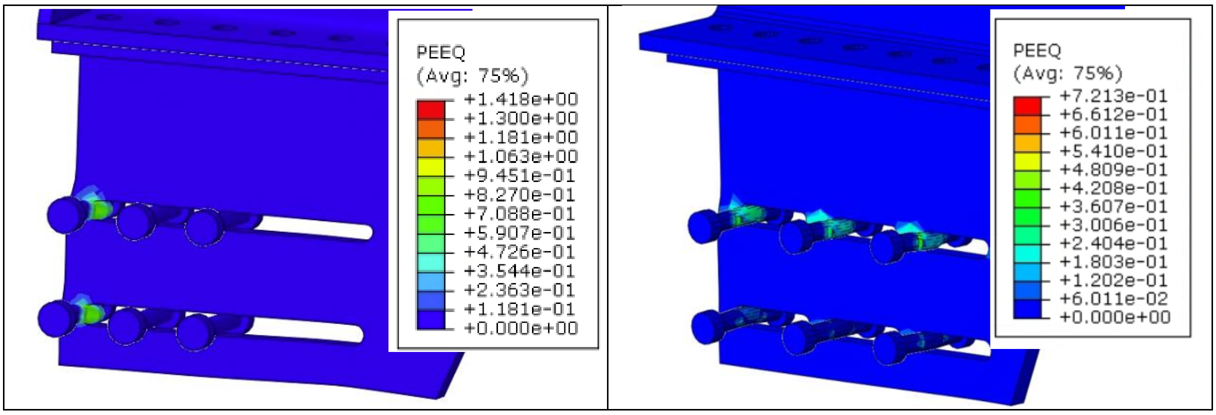

Figure 7: PEEQ distribution for the J-O joint haunch (left) and for the J-R joint haunch (right)

4.2 Column Loss Scenario

Second order bending moment over chord rotation curves for the joints J-O and J-R are plotted in *Figure 8*. The response of the frame under Column Loss Scenario is different with respect to the Monotonic Seismic Loading due to the boundary conditions. While the elastic branch of the connection *(Phase 1)* is the same, after the initial sliding the joints are characterized by a hardening/softening branch *(Phase 2)* depending on the direction of loading. When the SFC bolts get in contact with the slotted hole edges, a hardening branch is observed *(Phase 3)*.

The direction of loading affects the behaviour of the connection. The joint subjected to hogging bending moment exhibits greater resistance due to the strut and tie mechanism between the beam web and the haunch with L-stubs in compression. Contrarywise, when the joint is subjected to sagging bending moment (*Figure 9)* the L-stubs at bottom are prone to open and a degrading branch is registered.

J-O joints are characterized by the brittle failure of the T-stub bolts (in hogging) and high values of stresses are reached by the SFC bolts. The J-R joints are able to reach two times the ultimate rotation of the J-O joints before undergoing ductile failure. *Figure 10* shows a more even PEEQ distribution for the J-R joint with respect to the J-O.

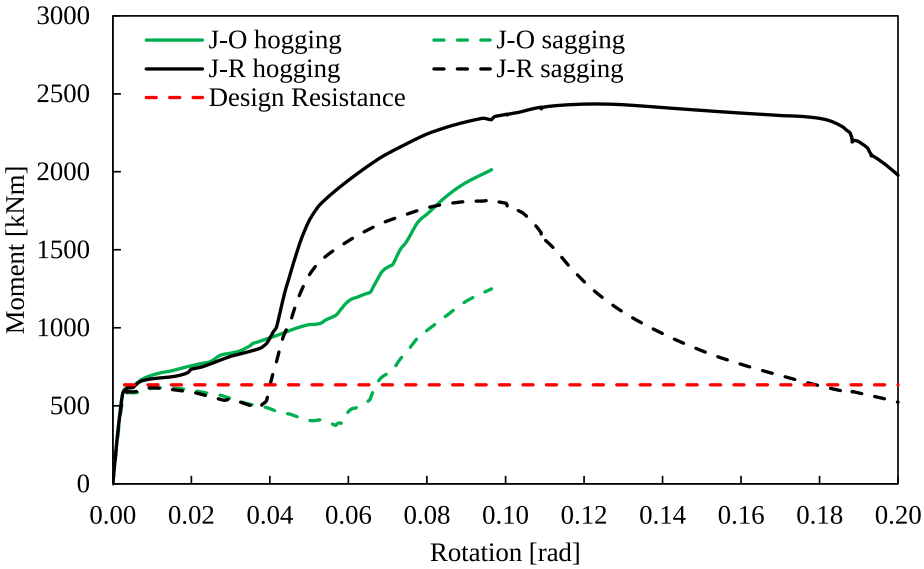

Figure 8: Moment-rotation curves under Column Loss Scenario for the J-O and J-R joints

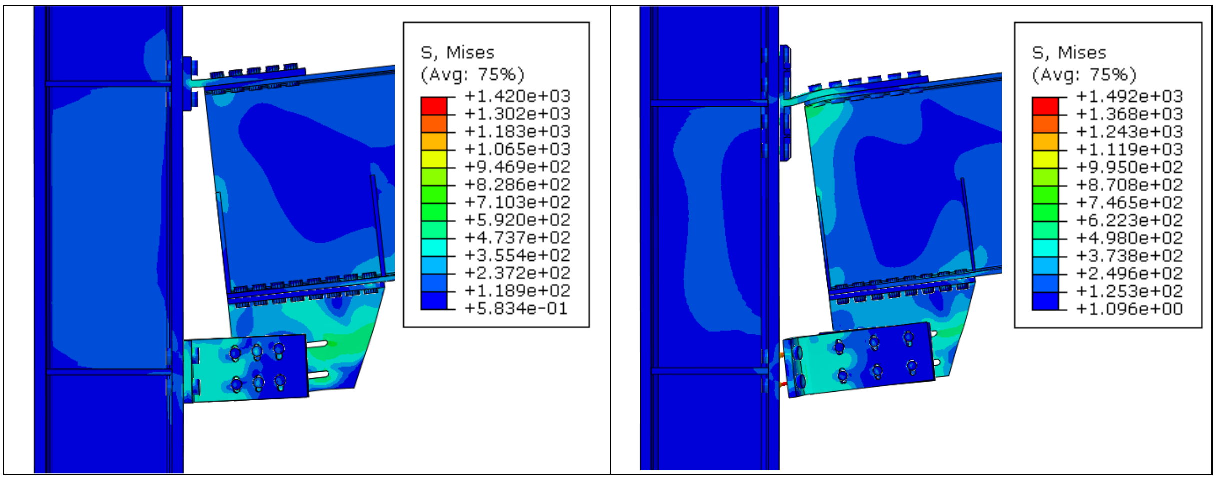

Figure 9: Von Mises stress distribution under the sudden removal of the left column, sagging bending moment; for the J-O joint (left), for the J-R joint (right)

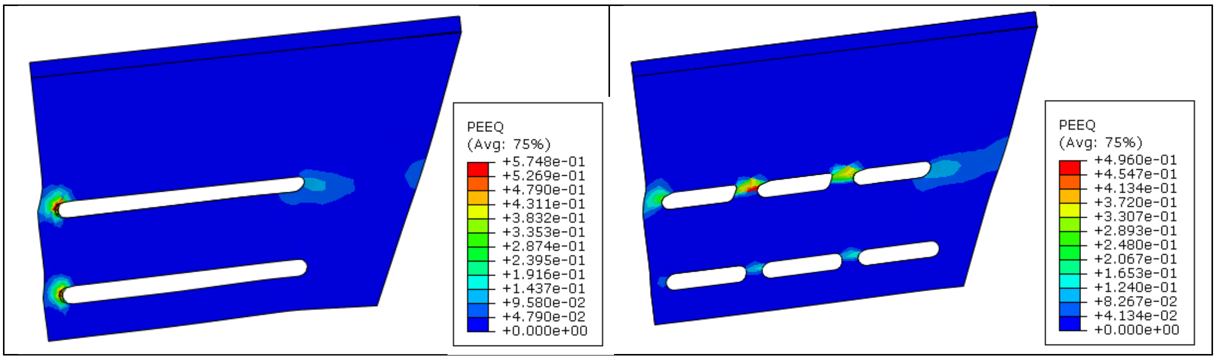

Figure 10: Equivalent plastic strain (PEEQ) distribution on the haunch under sagging action caused by sudden removal of a column by for the J-O joint (left) and for the J-R joint (right)

5 CONCLUSIONS

This study found that:

- The behaviour of a frame equipped with FREEDAM connection is almost the same under monotonic hogging and sagging moment. Conversely, its response under column loss scenario depends by the sign of the bending moment.
- The components of the friction device can be easily modified to answer specific needs. The T-stub can be reinforced in order to avoid brittle failure under column loss scenario and to reach larger rotations; the haunch can be designed with slotted holes for single bolts to shorten the resistance plateau, to anticipate the hardening branch of the connection and to ensure an even distribution of plasticization on the haunch.

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7 REFERENCES

[1] M. D'Aniello, R. Tartaglia, R. Landolfo, J-P Jaspart, J.F. Demonceau, Seismic pre-qualification tests of EC8-compliant external extended stiffened end-plate beam-to-column joints, *Engineering Structures*, 291, 116386, 2023.

[2] R. Tartaglia, A. Milone, M. D'Aniello, R. Landolfo, Retrofit of non-code conforming moment resisting beam-to-column joints: A case study. *Journal of Constructional Steel Research*, 189, 107095, 2022.

[3] A. Milone, R. Tartaglia, M. D'Aniello, R. Landolfo, Seismic upgrade of a non-code compliant multi-storey steel building: A case study. *Journal of Building Engineering*, 95, 110151, 2024.

[4] A. Prota, L. Fiorino, A. Nikpour, R. Landolfo, Test-Based Assessment of the Seismic Response of Bracing Systems for Concealed Grid Suspended Ceilings. *J. Earthq. Eng.*, 29(2), 339-367, 2025.

[5] A. Prota, R. Tartaglia, R. Landolfo, Influence of Column–Base Connections on Seismic Behavior of Single-Story Steel Buildings. *Buildings*, 14(11), 3606, 2024.

[6] F. Freddi, J.-R. Wu, M. Cicia, L. Di Sarno, M. D'Aniello, F. Gutiérrez-Urzúa, R. Landolfo, O.-S. Kwon, S. Bousias, J. Park, N. Stathas, E. Strepelias, Seismic Retrofitting of Existing

Steel Frames with External BRBs: Pseudo-Dynamic Hybrid Testing and Numerical Parametric Analysis. *Earthquake Engineering & Structural Dynamics*, 54, 3, 1064-1083, 2025.

[7] H.M. Garfamy, B. Mirzaie Abar, M. D'Aniello, Seismic Response of CFST Double-Tee Moment Connections: Design Criteria and Experimental Tests. *Engineering Structures*, 293, 15 October 2023, 116670

[8] R. Khani, Y. Hosseinzadeh, M. D'Aniello, M-H. Asl, Nonlinear response of coupled and tied-to-rigid base T-stub connections. *Journal of Constructional Steel Research*, 215, 108550, 2024.

[9] F. Ascione, M. D'Aniello, L. Feo, L. Granata, R. Landolfo, A novel ductile connection for FRP pultruded beam-to-column assemblies. *Composite Structures* 337, 118091, 2024.

[10] M. Latour, A. Sato, M. D'Aniello, R. Landolfo, G. Rizzano, Flexural response of metallurgically bonded steel-aluminium foam-steel panels and composite beams. *Engineering Structures*, 322, Part B, 1 January 2025, 119114.

[11] A. Campiche, R. Tartaglia, L. Fiorino, R. Landolfo, Experimental tests for the evaluation of the seismic performance of the innovative CFS wall, Thin-Walled Structures, 198, 2024, 111681.

[12] A. Poursadrollah, R. Tartaglia, L. Fiorino, S. Shakeel, R. Landolfo, Effect of lightweight steel partitions on seismic behaviour of moment resisting frames, *Journal of Constructional Steel Research*, 206, 2023, 107925.

[13] A. Milone, P. Foti, F. Berto, R. Landolfo, Post-necking and damage modelling of steel structural components: A comprehensive state of the art. *Engineering Structures*, 321, 118931, 2024.

[14] A. Milone, P. Foti, L.M. Viespoli, D. Wan, F. Mutignani, R. Landolfo, F. Berto, Influence of hot-dip galvanization on the fatigue performance of high-strength bolted connections. *Engineering Structures*, 299, 117136, 2024.

[15] A. Milone, P. Foti, S. Filippi, R. Landolfo, F. Berto, Evaluation of the influence of mean stress on the fatigue behavior of notched and smooth medium carbon steel components through an energetic local approach. *Fatigue and Fracture of Engineering Materials & Structures*, 46(11), 4315-4332, 2023.

[16] C.E. Grigorian, T.S. Yang, E.P. Popov, Slotted bolted connection energy dissipators, *Earthquake Spectra*, 9(3): 491–504, 1993.

[17] G.C. Clifton, *Semi-Rigid Joints for Moments Resisting Steel Framed Seismic Resisting Systems*. PhD Thesis, Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand, 417pp, 2005.

[18] G.A. MacRae, G.C. Clifton, H. MacKinven, N. Mago, J. Butterworth, S. Pampanin, The Sliding Hinge Joint Moment Connection. *Bulletin of the New Zealand Society for Earthquake Engineering*, 43(3): 202-212, 2010.

[19] H.-H. Khoo, G.C. Clifton, J.W. Butterwort, G.A. MacRae, S. Gledhill, G. Sidwell, Development of the self-centering Sliding Hinge Joint with friction ring springs. *Journal of Constructional Steel Research*, 78: 201–211, 2012a.

[20] H.-H. Khoo, G.C. Clifton, J.W. Butterworth, G.A. MacRae, G. Ferguson, Influence of steel shim hardness on the Sliding Hinge Joint performance. *Journal of Constructional Steel Research*; 72:119-29, 2012b.

[21] S. Ramhormozian, *Enhancement of the Sliding Hinge Joint Connection with Belleville Springs*, PhD Thesis, Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand, 237pp., 2018.

[22] S. Ramhormozian, G.C. Clifton, G.A. MacRae, H.-H. Khoo, The Sliding Hinge Joint: Final Steps towards an Optimum Low Damage Seismic-Resistant Steel System. *Key Engineering Materials*, 763: 751–760, 2018.

[23] H.H. Tjahjanto, *Bidirectional performance of steel beam to square concrete-filled steel tubular column connections*. PhD Thesis, Department of Civil and Environmental Engineering, University of Canterbury, Christchurch, New Zealand, 246pp., 2018.

[24] J.C. Chanchí Golondrino, *Hysteretic behaviour of Asymmetric Friction Connections (AFCs)*. PhD Thesis, Department of Civil and Environmental Engineering, University of Canterbury, Christchurch, New Zealand, 277pp., 2019.

[25] J.C. Chanchí Golondrino, G.A. MacRae, J.G. Chase, G.W. Rodgers, G.C. Clifton, Asymmetric friction connection (AFC) design for seismic energy dissipation. *Journal of Constructional Steel Research*, 157: 70-81. 2019.

[26] G. Ferrante Cavallaro, A.B. Francavilla, M. Latour, V. Piluso, G. Rizzano, Experimental behaviour of innovative thermal spray coating materials for FREEDAM joints. *Composites Part B: Engineering* 115: 289–99, 2016.

[27] M. Latour, M. D’Aniello, M. Zimbru, G. Rizzano, V. Piluso, R. Landolfo, Removable friction dampers for low-damage steel beam-to-column joints. *Soil Dynamics and Earthquake Engineering*, 115: 66–81, 2018.

[28] V. Piluso, G. Rizzano, M. Latour, R. Montuori, E. Nastri, A.B. Francavilla, S. Di Benedetto, R. Landolfo, M. D'Aniello, L. Simoes da Silva, A. Santiago, A.F. Santos, J.-P., J.F. Demonceau, *FREEDAM-PLUS – Seismic design of steel structures with FREE from DAMage steel connections*. 1st Ed, 978-92-9147-182-9, ECCS – European Convention for Constructional Steelwork. 300pp. https://www.steelconstruct.com/eu-projects/freedam-2/documents/ .2022.

[29] European Committee for Standardization (2005). EN 1993-1-8: 2005. Eurocode 3: Design of Steel Structures—Part 1-8: Design of Joints. European Committee for Standardization, Brussels.

[30] R. Tartaglia, R. Carlevaris, M. D’Aniello, R. Landolfo, Steel Beam-to-Column Friction Joint under a Column Loss Scenario. *Buildings*, 14 (3), 784, 2024.

[31] R. Tartaglia, M. D’Aniello, A. Campiche, M. Latour, Symmetric friction dampers in beam-to-column joints for low-damage steel MRFs. *J. Constr. Steel Res.*, 184, 106791, 2021.

[32] K. Kawashima, G.A. MacRae, J.-I. Hoshikuma, K. Nagaya, Residual Displacement Response Spectrum. *Journal of Structural Engineering*, 124(5): 523–530, 1998.

[33] PNRR RETURN. https://www.fondazionereturn.it/en/ (Accessed 20 March 2025).