Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – June 13-15, 2024
Paper No. 194
DOI: 10.11159/iccste24.194

Evaluating a Novel Yielding Damper for Enhanced Performance in Steel Beam-to-Column Connections

Mohammad Almohammad-albakkar[1], Zaid A. Al-Sadoon[2]
[1]Dept. of Civil Engineering, Al-Furat University
84C7+XHV, 7, Deir ez-Zor, Syria
m.albakkar@alfuratuniv.edu.sy
[2]Dept. of Civil & Environmental Engineering, University of Sharjah
P.O. Box. 27272, Al-Sharjah, UAE
zalsadoon@sharjah.ac.ae

Abstract **–** This study introduces the Radially Perforated Plate Damper (RPPD), a novel seismic resilience technology designed to enhance the performance of beam-to-column connections. Addressing critical issues such as insufficient ductility and energy inefficiency, the RPPD incorporates a radially perforated plate from which multiple steel strips extend, demonstrating yielding behavior at their extremities under story drift. This feature is pivotal for reducing the risk of plastic deformation in adjacent structural components. This research numerically investigates the cyclic lateral performance of a system integrating the RPPD with a steel beam-to-column connection using ABAQUS software. Preliminary findings reveal that the RPPD system maintains robust and stable hysteretic behavior, exhibiting consistent performance under tension and compression without significant strength degradation or pinching effects. Additionally, it effectively dissipates seismic energy and accommodates rotational demands up to 0.07 radians. Beyond performance enhancements, the RPPD offers notable advantages over existing dampers, including straightforward construction, ease of post-earthquake repair or replacement, and potential for cost-effective maintenance, presenting a significant advancement in seismic engineering practices.

Keywords**:** Beam-to-column connection; radially perforated plate damper; steel slit damper; finite element model; seismic performance

1. Introduction

In recent decades, the vulnerability of steel structures to seismic events has been starkly highlighted by the catastrophic damage and collapse witnessed during significant seismic episodes, such as the Northridge and Kobe earthquakes [1,2]. Subsequent in-depth analyses have consistently pinpointed the cause of these failures at the structural connections, with beam-to-column joints being particularly susceptible [3,4]. These investigations have illuminated a critical deficiency in seismic resilience, manifesting as inadequate ductility and energy dissipation capabilities, leading to brittle failures at beam-to-column moment connections due to the beams' limited plastic rotation capacity. Such failures underscore a significant shortfall in the seismic design paradigm, prompting many studies to augment the ductility and energy absorption characteristics of these critical connections [5]. This paper seeks to contribute to this ongoing discourse by addressing the identified gaps in understanding the seismic performance of steel structures, particularly focusing on enhancing the resilience of beam-to-column connections.

To effectively mitigate the challenges associated with the seismic performance of beam-column connections, this research explores innovative methodologies that enhance ductility and energy absorption capabilities. Central to this investigation is strategically manipulating the beam's plastic behavior and incorporating advanced damping technologies into moment connection designs. Dampers, recognized for their pivotal role in optimizing rotational capacity, stiffness, and connection strength, emerge as a superior strategy for addressing these engineering challenges [6-8]. A critical examination of beam modification techniques reveals the deliberate sectional reduction targeting either the beam flange [9,10] or web [11] as a mechanism to induce plastic hinges. This concept, originally introduced by Plumier (1990) by implementing trapezoidal cut profiles in beam flanges [12], has been further refined by subsequent studies. Maleki et al. (2012) notably extended this methodology to encompass cuts in both the web and flange, facilitating a transition to a plastic state that enables significant deformation while enhancing the plastic moment capacity and seismic energy dissipation through cyclic plastic excursions [13-15]. Extensive research has been conducted to enhance the seismic performance of CBFs. For instance, a buckling-restrained brace (BRB) is engineered and employed to bolster strength, stiffness, and ductility against lateral loads. BRBs mitigate structural damage and augment the braced structures' seismic resilience [16-19].

Steel slit dampers (SSDs) are crucial for enhancing the seismic resilience of buildings by absorbing energy and mitigating damage [20,21]. SSDs are celebrated for their ability to produce stable hysteretic behavior, owing to the inelastic deformation of their strips, alongside benefits such as lightness, ease of manufacture, and straightforward post-earthquake replacement [20]. Oh (1998) [22] introduced SSDs in the literature. This concept was further investigated and implemented experimentally by Chan and Albermani [23]. Who [23] developed a new steel energy dissipative device designed for earthquake protection of structures. This SSD is made from a standard structural wide-flange section with several slits cut into the web, forming a vierendeel truss arrangement. The device is weld-free, which eliminates the uncertainties and difficulties associated with in situ welding. Experimental results demonstrated that the device exhibits stable hysteresis with excellent energy dissipation and ductility. Its structural characteristics can be easily determined using fundamental engineering principles, allowing the design to be readily modified or extended to meet specific structural requirements [23]. Further advancements in the field have been marked by Oh et al.'s proposition of integrating SSDs within the bottom beam flange, presenting a novel approach to improving connection ductility and energy dissipation [24]. Köroğlu et al. have contributed to this discourse through the experimental and numerical evaluation of connections equipped with variously shaped steel slit dampers, affirming their efficacy in augmenting key performance metrics such as energy dissipation capacity, hysteretic behavior, and stiffness [25,26]. Most recently, Almohammad-albakkar and Behnamfar have introduced the grooved gusset plate damper (GGPD), a novel damper design aimed at bolstering the seismic resilience of cross-braced frames, which has demonstrated promising results in enhancing seismic performance [27,28].

This study presents the development of a novel yielding damper, designated as the Radially Perforated Plate Damper (RPPD), specifically engineered for integration into beam-to-column connections. The core aims of the RPPD are twofold: to act as a sacrificial element under seismic loading, akin to a fuse, and to facilitate energy dissipation. This innovative approach incorporates strategically placed grooves within the damper's design, which facilitate seismic energy absorption by promoting yielding at the plate's strip ends via in-plane bending. This mechanism is pivotal in enhancing the structural resilience of connections subjected to seismic events.

2. The Proposed Connection Damper

The Proposed System delineates an innovative seismic mitigation framework, encapsulating two pivotal components: the structural column and beam, alongside the Radially Perforated Plate Damper (RPPD), conceptualized as a seismic fuse. The RPPD is ingeniously engineered, comprising dual radially perforated plates, integrated with stiffeners, and a centrally positioned shaft exhibiting a radius denoted as r_1. For an elaborate elucidation of the novel connection, reference is made to Fig. 1. This figure further illuminates the design intricacy, showcasing the central region of the plate distinguished by a circular aperture, also with a radius of r_1, meticulously designed to house a shaft.

The operational mechanism of this connection is predicated on the moment forces at the heart of the connection, which instigates in-plane shear forces within the steel strips of the perforated plate. This shear stress precipitates a unique double-curvature in-plane flexural behavior in each strip. This dynamic response underlines a critical phenomenon where the strips may exhibit yielding at their termini when subjected to significant moment forces. This intricate interplay of structural elements underscores the system's potential to enhance seismic resilience through a meticulously designed energy dissipation mechanism, pivotal for the structural integrity of buildings subjected to seismic activities.

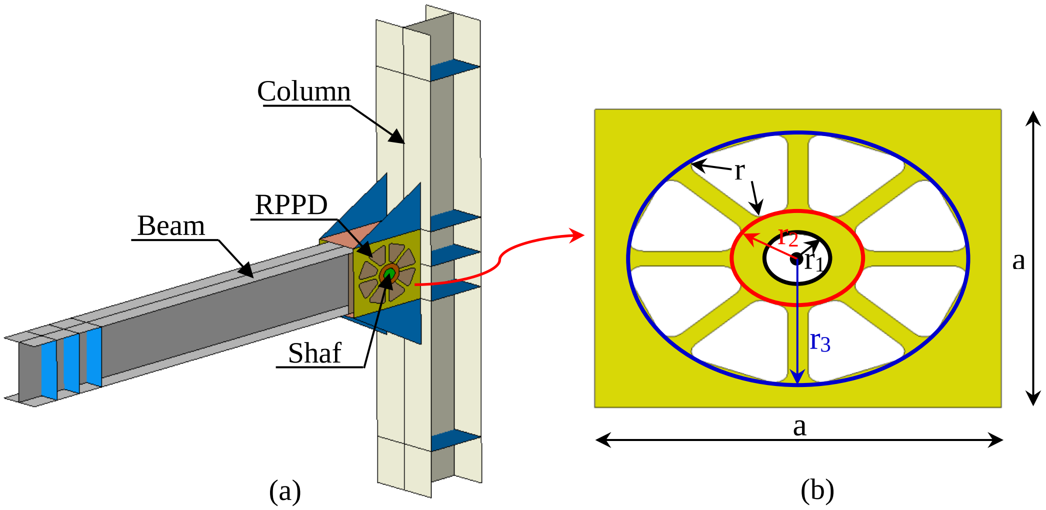

Fig. 1: Schematic view of the proposed connection; (a) assembly connection and (b) radially perforated plate damper (RPPD).

3. Numerical Investigation of the Proposed System

3.1. Modelling Techniques

This section explores the numerical modeling of the proposed system through finite element analysis, employing ABAQUS software for the simulation. The main structural components, namely the beam and column, are chosen based on standard IPB240 and IPE270 sections, respectively. These selections are visually represented in Fig. 2, laying the foundation for the simulation's geometrical parameters. The modeling assumptions delineate that, Radially Perforated Plate Damper (RPPD), subject to inelastic deformations under cyclic loading, all other system components are to remain within the elastic deformation range. This is a critical assumption for the integrity and reliability of the model, highlighting the focused investigation on the RFPDs' performance under specified loading conditions. Detailed specifications of the model, including dimensions (length, width, thickness) and the number of strips used, are tabulated in Table 1 and further illustrated in Fig. 3, providing a comprehensive overview of the model's physical characteristics. The material properties are defined in accordance with European standards for St37 steel, specifying a modulus of elasticity at 200 GPa, coupled with yield and ultimate stresses at 240 MPa and 370 MPa, respectively. These properties are essential for accurately simulating the material's behavior under load. An ultimate rotation threshold for connections is set at 0.07 rad, a crucial parameter for assessing the connection's performance under cyclic loading conditions.

Table 1: Dimensional properties of Radially Perforated Plate Damper (RPPD) (all dimensions, mm).

Parameter	n	h_t	b	t_d	r	r_1	r_2	r_3
Value	8	80	15	8	10	25	50	130

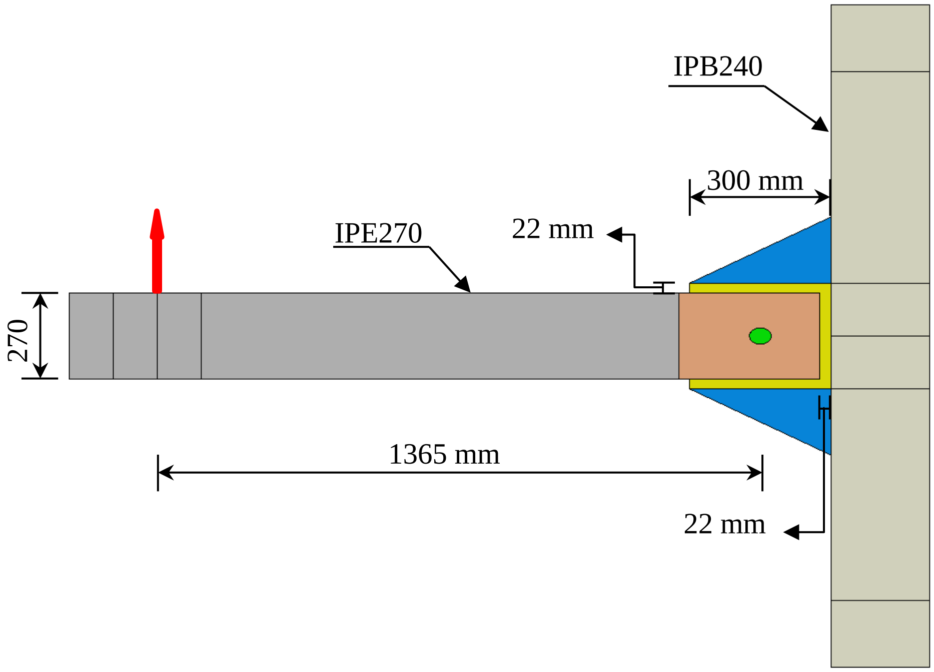

Fig. 2: Details of the innovative connection used in this study.

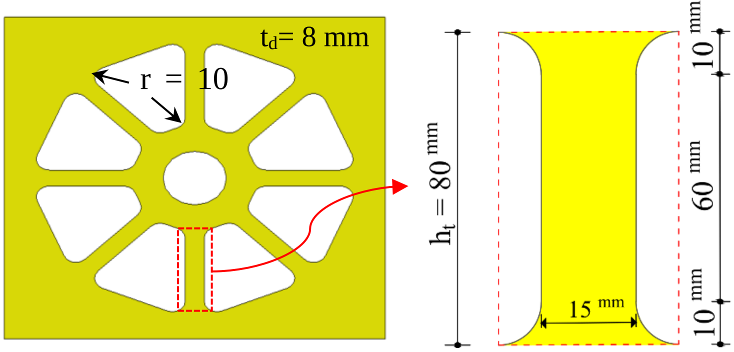

Fig. 3: Characteristics of the RPPD with specifications of its strips.

The finite element model utilizes shell elements, precisely the S4R element, for all connection components. This choice is instrumental in capturing the intricate stress distributions and deformations with high accuracy. The simulation protocol involves applying a vertical displacement history at the beam end and cyclic loading to mimic real-world loading conditions. This procedure adopts the SAC protocol, ensuring the analysis aligns with established seismic assessment criteria. Mesh discretization is meticulously defined, with a finer mesh size of 5 mm for the dampers to ensure detailed stress and deformation analysis, while a coarser 20 mm mesh is applied to other connection components. This strategic meshing approach, illustrated in Fig. 4, balances computational efficiency with the need for precision in areas of high stress concentration, particularly around the RFPDs.

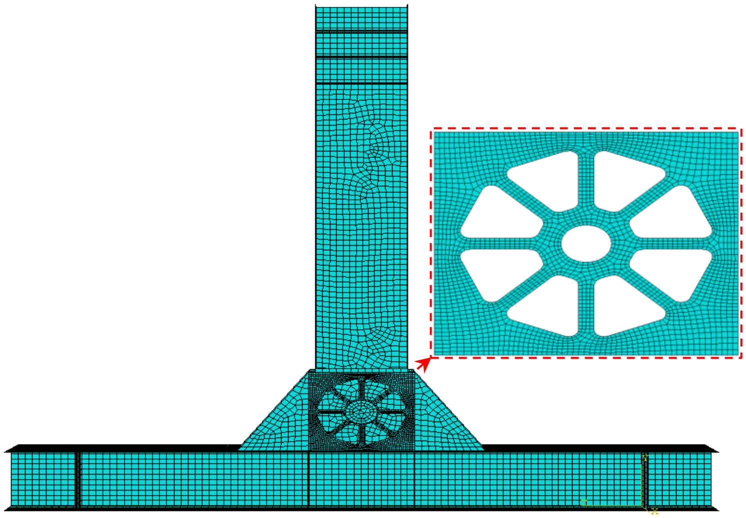

Fig. 4: The mesh configuration of the RPPD sample.

3.2. Results

The distributions of plastic strain (PE11) and equivalent plastic strain (PEEQ) across the novel connection are depicted in Figs. 5 and 6, respectively. A critical observation from the analyses is the uniform and symmetrical stress distribution across the perforated plate within the proposed system. Furthermore, a notable concentration of plastic strain at the termini of the strips is discerned. Examination of Figs. 5 and 6 reveals an absence of significant damage to other system components. Fig. 7 presents the load-displacement curve for the connection, incorporating the RPPD. The RRPD system exhibits lateral displacements compliant with the criteria for special moment frames, affirming its capability to maintain resilience. This performance is achieved without exhibiting pinching effects or degradation in stiffness and strength, thereby underscoring the system’s structural stability even under significant rotational demands. Additionally, Fig. 7 elucidates the proposed system's stable hysteretic behavior, which indicates its ability to undergo consistent performance under both tensile and compressive forces. This attribute enables the damper to accommodate larger rotations induced by seismic events, thus exceeding the prescribed design specifications.

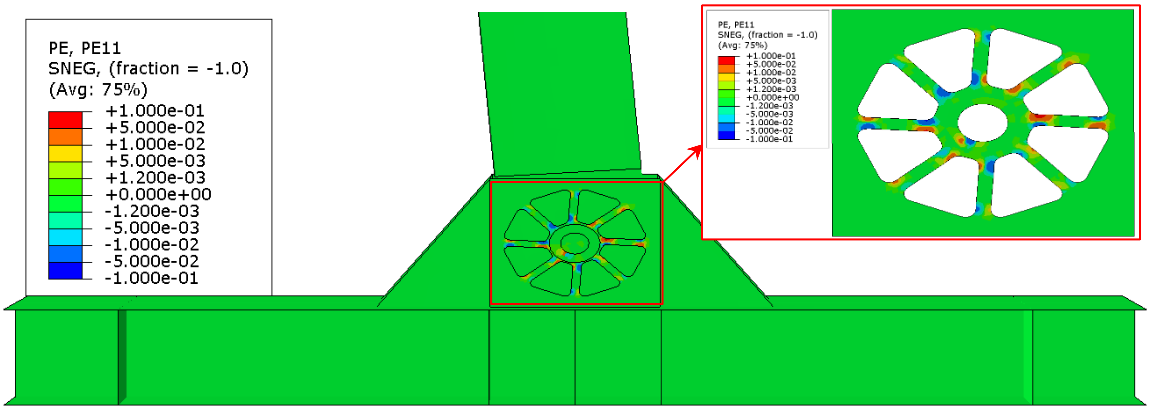

Fig. 5: Distribution of the PE11 in the RRPD system.

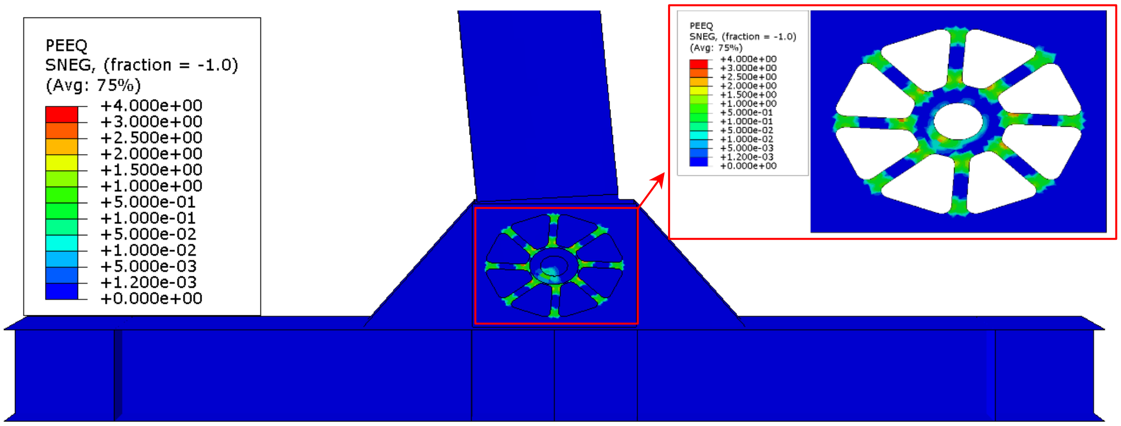

Fig. 6: Distribution of the PEEQ in the RRPD system.

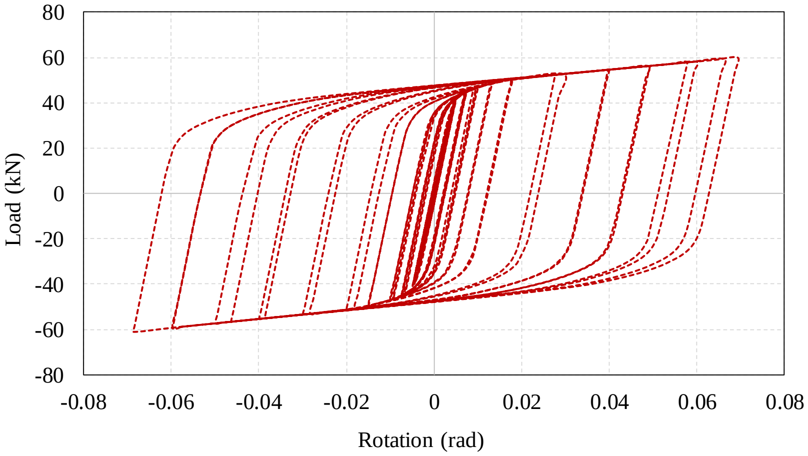

Fig. 7: Hysteresis curve of the RRPD system.

4. Conclusion

This study has introduced an innovative slit damper, termed the Radially Perforated Plate Damper (RPPD), engineered for integration within beam-to-column connections. It functions dually as a fuse and an energy dissipation mechanism. The design of the RPPD, distinguished by its radially arranged grooves, facilitates seismic energy dissipation via yielding at the ends of the strips induced by in-plane bending across the plate. The dynamic lateral response of the composite system, encompassing a steel beam-to-column connection augmented by the radially perforated plate damper, was meticulously examined through a series of numerical simulations conducted using ABAQUS software.

The insights gleaned from these simulations demonstrate that, under significant drift scenarios, plastic deformation is predominantly confined to the steel strips of the damper. Crucially, this deformation pattern is achieved without imparting noticeable damage to the damper's other structural components. An initial numerical exploration further indicated that the RPPD system exhibits robust and reliable hysteresis characteristics. The damper consistently performed under tensile and compressive forces, maintaining its structural integrity without significant strength degradation or pinching. Moreover, it demonstrated exceptional seismic energy dissipation capability and met rotational demands up to 0.07 radians. These findings accentuate the damper's design effectiveness, particularly in deformation attributes, and underscore its potential applicability in structural systems requiring such specialized responses. Acknowledging that this investigation represents a component of broader ongoing research efforts is pertinent.

References

[1] Mousavi H., Sabbagh Yazdi S. and Almohammad-Albakkar M., "A novel method for efficient design of frame structures equipped with nonlinear viscous dampers by using computational results of cylindrical friction damper", *Australian Journal of Structural Engineering*, vol. 24 no. 1 pp. 50-66, 2022.

[2] Ghanbari A., Mousavi H., Almohammad-albakkar M. and Habibi M.R., "Seismic Responses of Multi-Storey Structures Equipped with Linear and Nonlinear Viscous Dampers: A Comparison Study", *Available at SSRN 4253077*, 2022.

[3] Al-Sadoon Z.A., Leblouba M. and Fageeri A., editors. Experimental validation of a novel curved steel damper for steel frames with flexible beam-column joints. Structures; 2023: Elsevier.

[4] Behnamfar F. and Almohammad-albakkar M., "Development of Steel Yielding Seismic Dampers Used to Improve Seismic Performance of Structures: A Comprehensive Review", *International Journal of Engineering*, vol. 36, no. 4, pp. 746-775, 2023.

[5] Molavi R., Izadinia M. and Shahidi A.R., "Numerical and Experimental Studies on Cyclic Behavior of Beam-to-Column Connection with Yielding Steel Damper", *International Journal of Steel Structures*, vol. 20, no. 2, pp. 480-492, 2020.

[6] Leblouba M., Fageeri A. and Al-Sadoon Z.A., "A novel seismic energy dissipation device: Laboratory tests, mathematical modeling, and numerical analysis", *Soil Dynamics and Earthquake Engineering*, vol. 162, no. pp. 107493, 2022.

[7] Mousavi H., Sabbagh-Yazdi S.-R. and Almohammad-albakkar M., New mathematical formula for design viscous dampers in Internal and external Scissor-Jack braces, 6th International Conference on Interdisciplinary Researches in Civil Engineering, Architecture and Urban Management in 21st Century; Iran –Tehran2021.

[8] Al-Sadoon Z.A., Karzad A.S., Sagheer A. and AlHamaydeh M., editors. Replaceable fuse buckling-restrained brace (BRB): Experimental cyclic qualification testing and NLFEA modeling. Structures; 2022: Elsevier.

[9] Engelhardt M. and Husain A., "Cyclic-loading performance of welded flange-bolted web connections", *Journal of Structural Engineering*, vol. 119, no. 12, pp. 3537-3550, 1993.

[10] Morrison M., Schweizer D. and Hassan T., "An innovative seismic performance enhancement technique for steel building moment resisting connections", *Journal of Constructional Steel Research*, vol. 109, no. pp. 34-46, 2015.

[11] Hassanipour A., Rahnavard R., Mokhtari A. and Rahnavard N., "Numerical investigation on reduced beam web section moment connections under the effect of cyclic loading", *J Multidiscip Eng Sci Technol(JMEST)*, vol. 2, no. 8, pp. 2054-2061, 2015.

[12] Plumier A., editor New idea for safe structures in seismic zones. IABSE Symposium-Mixed Structures Including New Materials; 1990.

[13] Piluso V. and Rizzano G., "Experimental analysis and modelling of bolted T-stubs under cyclic loads", *Journal of Constructional Steel Research*, vol. 64, no. 6, pp. 655-669, 2008.

[14] Nader M. and Astaneh A., "Dynamic behavior of flexible, semirigid and rigid steel frames", *Journal of Constructional Steel Research*, vol. 18, no. 3, pp. 179-192, 1991.

[15] Maleki S. and Tabbakhha M., "Numerical study of slotted-web–reduced-flange moment connection", *Journal of Constructional Steel Research*, vol. 69, no. 1, pp. 1-7, 2012.

[16] Rafi M.M., Lodi S.H., Al-Sadoon Z.A., Saatcioglu M. and Palermo D., "Experimental investigation of dynamic behavior of RC frame strengthened with buckling-restrained bracing", *Journal of Structural Engineering*, vol. 148, no. 7, pp. 04022076, 2022.

[17] Karzad A.S., Al-Sadoon Z.A., Sagheer A. and AlHamaydeh M., "Experimental and Nonlinear Finite Element Analysis Data for an Innovative Buckling Restrained Bracing System to Rehabilitate Seismically Deficient Structures", *Data*, vol. 7, no. 12, pp. 171, 2022.

[18] Al-Sadoon Z.A., Karzad A.S., Sagheer A. and AlHamaydeh M., "Proof-of-Concept and Experimental Qualification for a Repairable Buckling-Restrained Brace (BRB)", *Proceedings of the Coordinating Engineering for Sustainability and Resilience (CESARE22), Irbid, Jordan*, vol. no. pp. 6-9, 2022.

[19] Rafi M., Lodi S., Al-Sadoon Z., Saatcioglu M. and Palermo D., "Shake-table testing of deficient reinforced concrete frame retrofitted with buckling restrained brace", *ACI Struct J*, vol. 118, no. 3, pp. 161-173, 2021.

[20] Al-Sadoon Z.A. and Almohammad-albakkar M., "Seismic Resilience of Steel-Braced Frames Incorporating Steel Slit Dampers: A Review and Comparative Numerical Analysis", *Civil Engineering Journal*, vol. 10, no. 4, pp. 1310-1335, 2024.

[21] Almohammad-albakkar M. and Behnamfar F., "Seismic Performance Assessment of Cross-Braced Steel Frame Equipped with New Damper", *13th International Congress on Civil Engineering*, 2023.

[22] Oh S.-H., "Seismic design of energy dissipating multi-story frame with flexible-stiff mixed type connection", *Tokyo University, Japan*, vol. no. pp., 1998.

[23] Chan R.W. and Albermani F., "Experimental study of steel slit damper for passive energy dissipation", *Engineering Structures*, vol. 30, no. 4, pp. 1058-1066, 2008.

[24] Oh S.-H., Kim Y.-J. and Ryu H.-S., "Seismic performance of steel structures with slit dampers", *Engineering structures*, vol. 31, no. 9, pp. 1997-2008, 2009.

[25] Köken A. and Köroğlu M.A., "Experimental study on beam-to-column connections of steel frame structures with steel slit dampers", *Journal of Performance of Constructed Facilities*, vol. 29, no. 2, pp. 04014066, 2015.

[26] Köroğlu M.A., Köken A. and Dere Y., "Use of different shaped steel slit dampers in beam to column connections of steel frames under cycling loading", *Advanced Steel Construction*, vol. 14, no. 2, pp. 251-273, 2018.

[27] Almohammad-Albakkar M. and Behnamfar F., "Numerical investigation of grooved gusset plate damper for using in cross-braced frames", *Journal of Constructional Steel Research*, vol. 196, pp. 107434, 2022.

[28] Almohammad-albakkar M., Behnamfar F. and Ataei A., "Experimental and numerical study of grooved gusset plate damper for cross-braced frames", *Journal of Constructional Steel Research*, vol. 216, pp. 108611, 2024.