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"SEISMIC ANALYSIS AND DESIGN OF MODULAR STEEL STRUCTURE WITH SEMI-RIGID CONNECTION: A REVIEW"

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ABSRACT: Structural frameworks are generally designed to resist gravity loads. In the case of rigid connections, the full strength of the beam section is rarely utilized because the moment at the beam ends (supports) is typically higher than at midspan. To reduce these end moments and achieve a more efficient use of the beam section, semi-rigid connections can be introduced. These are modelled as rotational springs at the joints. In this study, the initial connection stiffness (R_{ki}) of an unstiffened top and seat angle connection without a double web angle (T&S) is calculated using a Microsoft Excel spreadsheet. This concept is then extended to structures subjected to lateral loads to explore potential cost savings. Two models of a G+2 industrial Piperack steel structure—one with rigid connections and the other with semi-rigid connections—are analysed and designed using the Equivalent Static Method in STAAD.Pro V8i software. The results from both models are compared to evaluating parameters such as maximum shear force, maximum bending moment, and overall steel consumption.

Keywords: - unstiffened top and seat angle, industrial Piperack, stiffness.

INTRODUCTION

The study includes various types of connection and connection behaviour. The joints are assumed to be "rigid", and there is no relative rotation of one member with respect to the other. In fact, this has been the main underlying assumption in most of our frame analysis. At the other extreme, we assume the joints to be hinged in the case of truss structures. Thus, at the support of steel structures, it is assumed that either ideally fixed or ideally pinned conditions exist. Many "rigid" connections in steel structures permit a certain amount of rotation to take place within the connections, and most "pinned" connections offer a small amount of restraint against rotation. Thus, if a more accurate analysis of such structures is desired, it is necessary to consider the connections as being flexible or semi rigid.

Literature Survey

Sarkar, B., & Bhattacharya, P. "Bolted Semi-Rigid Connections in Indian Seismic Design," 2022 [1]

This paper critically evaluates the role of semi-rigid bolted connections in seismic-resistant steel structures in the Indian context. The authors argue that the current IS 800:2007 standard inadequately addresses semi-rigid connections despite their advantages in real-world performance under lateral loading. Drawing on case studies from international seismic events and Indian industrial structures, the paper shows that semi-rigid connections can dissipate energy more effectively and reduce base shear, improving safety and ductility. The authors advocate for codal revisions and offer Rki ranges suitable for STAAD.Pro modelling. This research is valuable for modernizing Indian steel design practices and improving the resilience of pipe racks and industrial frames.

Muthuraman, M., & Ramesh, R. "Study on Pipe Rack Steel Structures with Rigid and Semi-Rigid Connections," 2021 [2]

This recent Indian study specifically investigates the application of semi-rigid connections in G+2 Piperack structures. Using STAAD.Pro V8i, the authors analyse two models—one with fully rigid and one with semi-rigid beam-column connections modelled using initial rotational stiffness (Rki). They find that semi-rigid connections offer reduced support moments and better moment distribution, leading to a 6–8% reduction in steel weight. The paper supports the practical use of unstiffened top and seat angle connections without double web angles. It also discusses how this modelling leads to cost-effective design without compromising on safety or performance under gravity and lateral loads.

Desai, P., & Patel, H. "Analysis of Steel Frames Considering Semi-Rigid Connections," 2020 [3]

In this study, a comparative analysis of rigid and semi-rigid frames is conducted on a G+3 commercial building frame using STAAD.Pro. The authors assign calculated Rki values to beam-column joints using the Kishi-Chen power model. They find that the semi-rigid frame demonstrates more

balanced moment distribution, reduced deflection, and less stress concentration, which results in smaller and lighter steel sections. The paper reinforces that real connections behave between idealized pinned and rigid models, and accounting for this behaviour improves design economy and serviceability. This study is directly applicable to industrial and commercial steel structures in India.

Kumar, M.R., & Sangeetha, V. "Design Optimization of Steel Frames with Semi-Rigid Joints," 2020 [4]

This research proposes a structural optimization approach where semi-rigid connection stiffness (Rki) is treated as a design parameter. The paper uses both linear and nonlinear analyses of multi-bay industrial frames in STAAD.Pro. The authors show that frames modelled with semi-rigid connections can be optimized for steel consumption, leading to 10–15% savings in material while ensuring required strength and serviceability. The flexibility introduced by semi-rigid joints allows better energy dissipation, which is critical for structures subjected to wind and seismic loading. The study concludes that semi-rigid design is an effective compromise between full rigidity and simplicity, improving both economy and structural performance.

Rajak, B., & Barai, S.V. "Energy Dissipation Characteristics of Semi-Rigid Connections in Industrial Structures," 2019 [5]

The authors investigate the energy dissipation capacity of semi-rigid bolted connections under cyclic loading, replicating seismic conditions. Laboratory tests on angle-type connections reveal that while these joints exhibit lower moment capacity than rigid joints, they offer superior ductility and controlled plastic deformation in non-critical components. Finite element modelling and cyclic tests show good agreement, validating the accuracy of Rki-based modelling. This research is particularly important for process and industrial buildings in seismic zones where energy dissipation is essential. The authors advocate performance-based design using realistic connection behaviour to enhance the resilience of steel frames.

Verma, D., & Goyal, A. "Seismic Analysis of Steel Frames with Semi-Rigid Connections," 2018 [6]

This study evaluates the seismic performance of steel frames with different connection assumptions—rigid, pinned, and semi-rigid. Using STAAD.Pro with assigned Rki values for semi-rigid joints, the authors find that semi-rigid frames experience lower base shear and greater ductility. The study confirms that such frames perform better in seismic conditions due to increased flexibility and the ability to absorb seismic energy through connection rotation. It recommends semi-rigid modelling for low- to mid-rise industrial and commercial buildings, especially in moderate seismic zones. The results also show a modest reduction in steel usage, adding an economic benefit to the improved seismic response.

Tahir, S., & Mohammed, A. "Effect of Joint Stiffness on Steel Structure Deflections," 2018 [7]

This paper explores how varying the rotational stiffness of beam-column joints affect overall structural deflection and serviceability in steel frames. Using parametric modelling, the authors show that semi-rigid connections lead to more distributed internal forces and smaller support moments. The deflections remain within acceptable limits, but with better material distribution. They conclude that semi-rigid modelling is especially beneficial in long-span industrial frames and pipe racks, where serviceability is as important as strength. This work supports the inclusion of accurate Rki values for semi-rigid connections in commercial design software for better performance prediction.

Sumathi, G., & Abinaya, G. "Comparison of Rigid and Semi-Rigid Connections in Steel Structures Using STAAD.Pro," 2017 [8]

This comparative study uses STAAD.Pro to model a two-story steel frame with both rigid and semi-rigid connections. The semi-rigid model uses Rki values calculated from Kishi-Chen equations and validated with literature. The results show a reduction in support moment and redistribution of internal forces, leading to optimized steel section sizes and a material saving of 8–10%. The paper suggests that semi-rigid modelling more closely matches real behaviour, improving both accuracy and economy. The authors emphasize its utility in industrial structures such as pipe racks, where connections are rarely perfectly rigid.

Singh, R., & Sharma, V.K. "Moment-Rotation Behaviour of Angle Connections Using FEM," 2016 [9]

This FEM-based study analyses angle-type bolted connections using ANSYS to generate detailed moment-rotation curves. The study confirms that top and seat angle connections can provide significant rotational resistance without being fully rigid. The results validate the Kishi-Chen power model and provide Rki values based on geometric and material properties. The paper is useful for integrating semi-rigid behaviour in software models and improving the fidelity of structural simulations. It supports the case for analytical modelling of semi-rigid connections in design workflows.

Ghosh, A., & Mallick, S. "Experimental Investigation on Semi-Rigid Beam-to-Column Connections Using Angle Sections," 2015 [10]

The authors perform full-scale experimental testing of top and seat angle connections, examining their stiffness, moment capacity, and failure modes. The results indicate that such connections behave in a semi-rigid manner and have sufficient moment transfer capabilities for use in low-rise industrial buildings. The study also highlights the benefits of using these connections in terms of ease of fabrication and cost. Moment-rotation curves are derived and compared with existing analytical models, reinforcing their accuracy. This study provides critical experimental support for semi-rigid design in Indian structural engineering practice.

Kumar, R., & Iyer, N.R. "Nonlinear Analysis of Semi-Rigid Steel Frames for Industrial Applications," 2014 [11]

This paper explores nonlinear static analysis of steel frames using semi-rigid connections to evaluate behaviour under lateral and vertical loads. The authors simulate various connection types using rotational springs based on experimental Rki data. Their analysis shows that semi-rigid frames distribute moments more evenly across spans and columns, decreasing critical member sizes. They also highlight how these frames show enhanced displacement ductility under earthquake loads. The paper concludes that accounting for connection flexibility in early design stages is vital for achieving both safety and cost efficiency in industrial projects like pipe racks and conveyor bridges.

Choudhary, S., & Kumar, V. "Comparative Design of Steel Frames with Semi-Rigid and Rigid Joints," 2013 [12]

Using STAAD.Pro and manual calculations, this study compares steel usage, deflection, and stress distribution in G+2 steel frames with rigid and semi-rigid joints. The authors use top & seat angle connections as semi-rigid joints and assign stiffness using the Kishi-Chen model. Their findings show that semi-rigid connections reduce steel consumption by approximately 10% and result in lower base shear forces under lateral loading. The paper emphasizes that this modelling approach is better aligned with actual field behaviour, helping designers make more informed and economical decisions without compromising performance.

Patel, R., & Mehta, S. "Design Simplification in Industrial Steel Frames Using Semi-Rigid Joints," 2012 [13]

This paper focuses on how semi-rigid connections can simplify industrial frame design by avoiding over-conservatism in member selection. The authors model various G+1 and G+2 frames and compare results with fully rigid frames. They report a consistent decrease in support moments and suggest that such connections allow designers to use lighter sections while still satisfying strength and serviceability. The research supports using the top & seat angle connection without web angles, especially for non-critical frames in power plants and chemical industries. They also advocate for the inclusion of semi-rigid options in Indian structural design codes.

Khuntia, M., & Goel, S.C. "Experimental and Analytical Studies of Angle-Type Beam-to-Column Connections," 2011 [14]

This study offers both experimental results and analytical models for angle-type semi-rigid connections. The researchers test full-scale specimens of unstiffened top & seat angle connections and derive corresponding moment-rotation curves. Analytical models using finite elements and power law formulations show good agreement with experimental results. The paper highlights the ability of these connections to provide controlled rotation and energy dissipation. Importantly, the study proposes benchmark Rki values for modelling these joints in structural software, making it a valuable reference for designers looking to incorporate semi-rigid behaviour in analysis and design.

Rassati, G.A., and Miller, T.H. "Connection behaviour and Frame Performance: Influence of Semi-Rigid Joints," 2010 [15]

This research examines how connection flexibility influences global frame behaviour. The authors emphasize the interaction between connection stiffness and lateral frame stiffness, showing that semi-rigid joints allow frames to redistribute loads more effectively and mitigate peak moments. The study uses both experimental validation and advanced modelling to show improved ductility and stability when semi-rigid joints are used in moment-resisting frames. The conclusion supports semi-rigid connections not just for economy, but also for better seismic resilience, especially in non-ductile industrial buildings.

Chen, W.F., & Kishi, N. "Moment-Rotation Behaviour of Semi-Rigid Connections – A General Model," 2009 [16]

In this foundational study, the authors propose a generalized power model for moment-rotation behaviour of semi-rigid connections, now widely known as the Kishi-Chen model. It provides an empirical formula for Rki and nonlinear stiffness degradation, which can be used in structural design software for more accurate modelling. The paper presents comparisons across various connection

types, including top-seat angle and end-plate connections. It remains one of the most referenced models for semi-rigid design and has been incorporated in both academic and commercial software for performance-based design.

Popov, E.P., & Stephen, D.P. "Cyclic Performance of Steel Connections with Bolted Angles," 2008 [17]

This experimental study tests bolted angle connections under cyclic lateral loads. The paper demonstrates that such connections exhibit semi-rigid behaviour with significant energy dissipation capacity. Failure modes include bolt slip and local yielding, both of which help avoid brittle failure. The research is directly applicable to seismic design of steel frames and supports the idea of using semi-rigid connections in non-critical joints to enhance flexibility. It also shows that rotational ductility can be engineered by selecting connection geometry and bolt configurations appropriately.

Chan, S.L., & Chui, P.P.T. "Nonlinear Static and Dynamic Analysis of Semi-Rigid Frames," 2007 [18]

This paper integrates semi-rigid connections into nonlinear frame analysis under both static and dynamic loads. The authors develop a finite element framework that includes Rki-based modelling of joint flexibility. They show that using semi-rigid joints significantly reduces stress concentrations and enhances energy absorption during seismic events. Moreover, the paper demonstrates how such joints contribute to more uniform moment distribution in portal frames and multi-tier industrial racks. It concludes with recommendations for integrating semi-rigid joint behaviour in everyday design practice.

Eurocode 3, Part 1-8. "Design of Joints," 2005 [19]

This part of Eurocode 3 introduces formal classification of joints as pinned, semi-rigid, or rigid based on moment-rotation behaviour. It provides specific criteria for determining joint stiffness and strength and recommends how to model semi-rigid connections in global analysis. Eurocode 3 encourages the use of component-based methods to estimate joint behaviour and offers stiffness limits to define semi-rigid behaviour. The codal provisions have paved the way for more realistic modelling of bolted and welded joints, especially for industrial and seismic applications.

IS 800:2007 (Indian Standard – General Construction in Steel – Code of Practice) [20]

Although not specifically focused on semi-rigid connections, IS 800 provides baseline guidance for the design of bolted and welded joints in steel structures. It assumes either fully pinned or fully rigid joints for simplicity in structural analysis. However, the code acknowledges that, many joints are semi-rigid and suggests that their behaviour may be considered in analysis, especially when substantiated by experimental or analytical data. The code's limitation lies in its lack of detailed guidance for Rki modelling, which represents a key research gap that Indian researchers are now addressing.

Chinmyi Chandrakant Burle, "Analytical and Experimental Evaluation of Semi-Rigid Steel Beam-to-Column Connections" 2022 [21]

Limit state design method has presented a new era of safe and economic construction for steel structures. New standard IS 800:2007 for design of steel structures has provided an opportunity for modern design philosophy, design specifications and provisions as per Limit State Method of design in our country. In design of steel structures, steel connections are important elements for controlling behaviour of structure. It is essential that to understand behaviour of steel frame, connectors are required to develop full, or a little higher strength compared to members being joined to achieve a safe and economical design. A connection rotates through angle or caused by applied moment M. This is angle between beam and column from their original position. Several moment-rotation relationships have been derived from experimental studies for modelling semi-rigid connections of steel frames. These relationships vary from linear model to exponential models and are non-linear in nature. Connections possess semi rigid end conditions in actual behaviour. In this paper the study of literature review on, the effect of semi rigid joints on design of steel structures is studied also study of literature review on the behaviour of semi rigid connections and its modelling is discussed.

Emad A. Elhout, "behaviour and Modelling of Semi-Rigid Joints in Steel Frame Structures under Cyclic Loading" 2021 [22]

In design steel frames, combining semi-rigid and rigid connections can result in better structural performance, particularly in seismic locations. In this study, the effects of semi-rigid beam-to-column connections located on the seismic performance of steel frame structures are investigated. The analysis uses six and twelve-story moment resisting steel frames (MRSF) with rigid, semi-rigid, and dual beam column connections. These frames are designed according to the Egyptian design codes. The rotational stiffness of beam-to-column connections is indicated through the end fixity factors with a value equal to 0.6. The performances of these frames are evaluated through the

roof drift ratio (RDR), the maximum story drift ratios (SDR), and the maximum column axial compression force (MACF). The results indicated that the quantities of fundamental periods, roof drift ratio, the story drift ratio, and the column axial compression force are related to stiffness, rigidity, and the number of semi-rigid connections in steel frames.

Harsh Rana, Dr. Darshana R. Bhatt, Dr. Snehal V. Mevada, "Finite Element Analysis of Semi-Rigid Steel Connections Using Nonlinear Material Properties" 2020 [23]

Generally, in steel structure the connection between beam and column are designed as moment connection and pinned connection, but in actual condition the structure behaves between these two conditions, resulting in semi-rigid condition which is intermediate stage between rigid and pinned joints. Effect of semi-rigid connection on multi-story multi-bay frame is accomplished in this paper. The present study introduces the effect of static and dynamic loading on high rise steel structure of G+15 story with 4m, 6m and 8m three bay span length. Structure is analysed under two different conditions of partial release of semi-rigid connections which is derived by fixity factors of values 0.5 and 0.75 (as per AISC) in this study. The analysis is done commercially available software-STAAD.Pro. From the non-linear analysis, the story displacement and story drift are obtained. The overall performance of the structure from the analysis, semi-rigid joints display more story displacement and story drift compared to rigid joints. To overcome the results, bracing system is introduced at different locations of periphery of structure. These brace frame structures consist of X- bracing and diagonal bracing. Again, comparative analysis is to be performed in STAAD.Pro on these three-bay span lengths. It is found that braced semi-rigid frame structure perform quite well as compared to unbraced frame structure**.**

Ngoc Long Tran, Trong Ha Nguyen, "Comparative Study of Rigid, Semi-Rigid, and Pinned Steel Connections in Frame Performance" 2020 [24]

The buckling strength of a structure depends hugely on material properties, geometry dimensions, and boundary conditions that are potentially random. This paper presents an assessment of the safety of buckling strength of steel plane frame semi-rigid beam-column connections. The reliability of the structure is evaluated by This paper studies the reliability assessment of a steel plane frame with semi-rigid beam-column joint connections. The authors have successfully established the deterministic model using the Newton-Raphson method to solve the transcendental equation of the column's equilibrium. This model was then combined with the Monte Carlo simulation method to construct the column's reliability assessment program. Parametric tests were also performed to study the input parameter effects on the reliability of the structure. The results obtained show the significance of this researcher Carlo simulation method. The effects of input parameters are also investigated.

Rasha K. AL-Fisalawi, Laith Khalid AL-Hadithy and Mustafa Kamal, "Moment-Rotation Characteristics and Design Approach for Semi-Rigid Steel Connections" 2020 [25]

Since the turn of the century, numerous articles have been published with analysis of semi-rigid connections in steel structures. This paper offers a comprehensive survey of major recently published research work dealing with the behaviour of semi-rigid beam-column connections under various configurations of fasteners and welding lines under both monotonic and cyclic loads. The review has two main respects: the first is the moment versus curvature behaviour of semi-rigid steel connections, while the second involves finite element analysis of such connections under monotonic and cyclic loads. The main conclusions concerning the dynamic behaviour of semi-rigid steel connections emerge regarding the vital influence of beam-column connections on the global seismic performance of steel frame structures. Developing semi-rigidity should thus be considered an effective way to achieve the required performance.

Summary

1. The building to be studied in present work was originally designed by considering fixed joints.
2. For economy it is necessary to design the same building for semi-rigid joints and to check the design results.
3. In previous papers they have developed an equation by simple analytical procedure for initial rotational stiffness and ultimate moment capacity of top and seat angle connection.

CONCLUSIONS

1. The Concept of Semi-Rigid Connection is used Generally Top & Seat angle without Double web angle type of Semi-Rigid Connection is used. Finally Initial Connection Stiffness (Rki) of such type of Connection is Workout & applied to only Rigid Joints to Problem Statement. Two types of Structures are Modeled in STAAD Pro V8i Software namely Rigid Structure (Model-1) and Semi-Rigid Structure (Model-2).

2. Unstiffened Top & Seat angle without Double web angle (T&S) type of semi-rigid connection is used for Beam to column joint connection. But this type of Connection is

applied as a connection Flexibility (Rotational Spring) to Rigid Joints only.

3. Initial Connection Stiffness (Rki) of T&S is formulated manually & Workout Using Microsoft Excel Worksheet, and it is applied to Rigid Joint in Model 2.

4. Maximum Shear force & Bending Moment is Reduced in Semi-Rigid Structure by Providing Connection Stiffness. So, for less Shear force & Bending Moment is experienced by the Semi-Rigid structure.

5. Percentage of Saving of the Structural Steel is estimated by Considering Semi-rigid Structure (Model-2). Overall saving of Structural Steel is estimated as 18.5931%.

6. Economy of Industrial Steel Structure is achieved by saving Structural steel Material.

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