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A study to Improve the Rigidity of Beam-to-Column Connections in Reinforced Concrete Frames for Residential Buildings

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Abstract:
The construction of residential buildings in Libya has become increasingly expensive, necessitating cost-effective design solutions. Structural engineers play a critical role in reducing construction costs while ensuring safety and efficiency. One approach to achieving an optimal design is minimizing the dimensions of structural elements, a critical factor influencing structural performance and economy is the rigidity of beam-to-column connections, which significantly affects deformations and then internal forces. According to beam bending theory, bending moments and shear forces are directly proportional to deformation. Therefore, reducing primary curvature leads to a decrease in design moments, allowing for more economical structural sections. This study investigates the impact of considering partial rigidity in beam-to-column connections within reinforced concrete (RC) frames, particularly for single-story buildings. In conventional structural design, connections are often assumed to be either fully rigid or fully pinned, neglecting partial rigidity effects. This oversimplified modelling approach results in overdesign and increased material consumption, deviating from sustainability principles. The research uses SAP2000 structural analysis software to assess various degrees of connection rigidity and their influence on member deformation. The findings indicate that incorporating realistic connection rigidity can reduce beam deformation by up to 20% (at 0.7 rigidity), leading to smaller and more cost-effective frame sections. Furthermore, common construction methods in the state of Libya inherently provide a certain degree of rigidity at beam-to-column interfaces,

yet current design practices often overlook this advantage. This study underscores the importance of optimizing beam-to-column connection rigidity to enhance structural performance, reduce material usage, and align with sustainable design principles. The findings contribute to improving cost efficiency in RC frame construction, providing valuable insights for engineers seeking to optimize structural design in residential buildings

Keywords: Beam-to-Column, Connection, Sustainability, Optimum Design, Rigidity

دراسة لتحسين صلابة (جساءة) وصلات العتبات بالأعمدة في إطارات الخرسانة المسلحة للمباني السكنية

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الملخص

أصبح تشييد المباني السكنية في ليبيا أكثر تكلفة بشكل متزايد، مما يستدعي إيجاد حلول تصميمية اقتصادية. يلعب المهندسون الإنشائيون دورًا محوريًا في خفض تكاليف البناء مع ضمان السلامة والكفاءة. تتمثل إحدى طرق تحقيق التصميم الأمثل في تقليل أبعاد العناصر الإنشائية مع الحفاظ على معايير الأمان المطلوبة. تعتبر صلابة اتصال العتبات بالأعمدة عاملًا أساسيًا يؤثر بشكل مباشر على الأداء الإنشائي للمباني وكلفة انشائها ، حيث يؤثر بشكل كبير على التقوس ومن تم على القوى الداخلية التصميمية. وفقًا لنظرية انحناء العتبات، فإن عزوم الانحناء وقوى القص تتناسب طرديًا مع التشوه. وبالتالي، فإن تقليل التقوسات الأولية يؤدي إلى انخفاض العزوم التصميمية، مما يسمح باعتماد مقاطع إنشائية أكثر اقتصادية. تبحث هذه الدراسة في تأثير أخذ الصلابة الجزئية في الاعتبار عند تصميم وصلات العتبات بالأعمدة في الاطارات الخرسانة المسلحة لمباني ذات الطابق الواحد. في التصميم الإنشائي التقليدي، تُفترض وصلات إما صلبة تمامًا أو مفصلية تمامًا، مما يؤدي إلى إهمال تأثير الصلابة الجزئية. يؤدي هذا النهج التبسيطي إلى زيادة في الابعاد التصميمة والاستهلاك المفرط للمواد، مما يتعارض مع مبادئ الاستدامة. تستخدم هذه الدراسة برنامج التحليل الإنشائي SAP2000 لتقييم تأثير درجات

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مختلفة من صلابة الوصلات على تشوه العناصر الانشائية وتوزيع القوى الداخلية. تشير النتائج إلى أن أخذ الجساءة الجزئية في الاعتبار يمكن أن يقلل من تشوه العتبات بنسبة تصل إلى 20٪ (عند صلابة 0.7)، مما يؤدي إلى استخدام مقاطع هيكلية أصغر وأكثر كفاءة من حيث التكلفة. علاوة على ذلك، توفر أساليب البناء الشائعة في ليبيا درجة معينة من الصلابة في مناطق اتصال العتبات بالأعمدة، إلا أن الممارسات التصميمية الحالية غالبًا ما تتجاهل هذه الميزة. تؤكد هذه الدراسة على أهمية تحسين مرونة وصلات العتبات بالأعمدة لتعزيز الأداء الإنشائي، وتقليل استهلاك المواد، وتحقيق مبادئ التصميم المستدام. تساهم النتائج في تحسين الكفاءة الاقتصادية لإنشاء إطارات الخرسانة المسلحة، وتوفر رؤى قيمة للمهندسين الساعين إلى تحسين التصميمات الهيكلية للمباني السكنية.

الكلمات المفتاحية :االوصلات بين الكمرات والاعمدة ، الاستدامة، ، التصميم الأمثل، الصلابة.

Introduction

The construction industry in the state of Libya, like many developing countries, faces increasing pressures due to the rising cost of building materials, labour, and energy. The demand for residential buildings continues to grow, driven by population expansion and urbanization. However, the increasing cost of construction materials and resources, particularly in the context of ongoing economic challenges, has made the development of affordable housing projects more difficult. To address these challenges, structural engineers are tasked with finding innovative and cost-effective solutions that can both maintain the safety and functionality of buildings while optimizing material usage [1]. One such approach is the optimization of structural design, particularly focusing on minimizing material consumption without compromising safety or performance. Among the many factors influencing the cost of construction, the design and behavior of structural elements such as beams and columns are of significant importance, especially in reinforced concrete (RC) frame construction, which is widely used in residential buildings [2].

Reinforced concrete frames, composed of beams and columns, form the core structural system for most mid-rise and low-rise residential buildings in the state of Libya. These buildings typically face static loads from the building's weight, live loads, and environmental factors such as wind and some seismic forces. The connection

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between beams and columns plays an important role in determining the overall performance of the structure. It influences the distribution of internal forces, the stability of the frame, and the overall deformation of the structure. The rigidity of these beam-to-column connections is therefore a critical parameter that directly affects the internal force distribution and the deformation patterns in the structure [3]. Conventionally, these connections are modelled in one of two ways: as fully rigid or fully pinned, both of which are idealized conditions that often do not accurately reflect the true behaviour of these connections under loading. Such oversimplified models often result in an inefficient design that either overestimates or underestimates the required structural capacity, leading to increased material consumption and, consequently, higher construction costs.

Beam bending theory, which is fundamental to the analysis and design of reinforced concrete beams, establishes that the bending moment and shear force within a beam are directly proportional to its deformation [4]. This relationship is critical to understanding how a reduction in primary displacements can lead to more efficient designs. Specifically, minimizing beam deflection leads to a decrease in the design bending moment, which can result in smaller, more economical structural sections. The optimization of the beam-to-column connection rigidity offers a potential solution to this issue. By considering partial rigidity in these connections, rather than assuming them to be either fully rigid or fully pinned, it may be possible to reduce beam deformation, thereby decreasing design moments and optimizing the size of structural elements. This approach not only enhances structural efficiency but also aligns with the goals of reducing material usage and promoting sustainability in construction practices [5]. Principally, The rigidity behaviour of beam-to-column connections defines the rotational stiffness of the joint, which governs the moment distribution, structural continuity, and global stability of the frame. It is characterized by the moment-rotation relationship, influencing the overall frame response under static and dynamic loading conditions. Accurate modeling of this behaviour is essential for predicting structural performance, and optimizing design efficiency [6].

The impact of beam-to-column connection rigidity on the overall performance of RC frames has been the subject of various studies, yet the application of such research in the context of Libyan

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residential buildings remains limited. While partial rigidity in connections is often considered in more advanced structural analyses, many traditional design practices continue to rely on simplified assumptions that do not account for the complex behaviour of these connections under real-world loading conditions. This oversight can result in designs that overestimate the strength and stiffness of connections, leading to overdesign and unnecessary material use. The prevailing design approach, which assumes idealized connection behaviour, is thus in need of refinement to reflect more realistic connection rigidity models.

The primary aim of this study is to investigate the effect of incorporating partial rigidity in beam-to-column connections for RC frames, specifically in the context of single-story residential buildings in the state of Libya. This research evaluates the influence of various degrees of connection rigidity on beam deformation and internal force distribution using the SAP2000 structural analysis software [7]. SAP2000 is a widely used, advanced software tool that can model and analyze structural systems with a high degree of accuracy. By simulating different connection rigidity conditions, the software allows for a more detailed understanding of the behaviour of RC frames and the potential benefits of accounting for partial connection rigidity.

The results of the study indicate that incorporating realistic degrees of beam-to-column connection rigidity can lead to a significant reduction in beam deflection, with reductions of up to 20% (at 0.7 rigidity). This reduction in deformation not only enhances the overall performance of the structure but also leads to more efficient use of materials. In practical terms, this means that the size of beams and columns can be reduced while still maintaining the required safety and serviceability standards. This has the potential to result in substantial cost savings in the construction of residential buildings. Furthermore, the study highlights that typical construction practices in the state of Libya, which often involve the use of cast-in-place connections, inherently provide a certain degree of rigidity at the beam-to-column interface. However, current design practices tend to neglect or overlook this advantage, leading to unnecessary material consumption.

In summary, this study presents an innovative approach to the design of reinforced concrete frames in residential buildings in the

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state of Libya by considering the impact of partial beam-to-column connection rigidity. Through the use of advanced structural analysis software, the research demonstrates the potential benefits of incorporating realistic connection behaviour into the design process, leading to more cost-effective, sustainable, and efficient construction practices. The findings provide valuable insights for engineers and designers working in the context of residential building construction in the state of Libya and similar regions, offering a pathway toward optimizing structural design for both cost efficiency and sustainability. This research ultimately underscores the importance of refining traditional design practices to account for the true behaviour of structural connections, paving the way for more economically viable and environmentally responsible building solutions.

Problem Statement

The construction industry in Libya faces significant challenges due to rising material costs, labour expenses, and increasing demand for residential buildings. Traditional design practices for reinforced concrete frames often assume idealized beam-to-column connections, leading to inefficiencies and unnecessary material consumption. This study aims to optimize these connections by incorporating realistic partial rigidity, improving structural performance, reducing costs, and enhancing sustainability in residential construction .This study investigates the impact of beam-to-column connection rigidity on the design forces of reinforced concrete structures. Using SAP2000, different levels of connection rigidity (0% to 100%) are modelled to assess their effects on internal force distribution and structural performance [8]. Initial findings indicate that considering connection rigidity can reduce design forces highlighting its potential for more economical and sustainable structural design practices.

Modelling

The dimensions and sections of the concrete frame for a typical residential building were selected, with the vertical load representing the roof loads. The lateral load was imposed as a nominal value to ensure that the simulation accounts for all loading considerations. This conventional reinforced concrete structural frame was studied (see Figure 1) for different rigidity levels of beam-to-column connections (0.0, 0.25, 0.50, 0.75, 1.0) which define the rigid zone factor.

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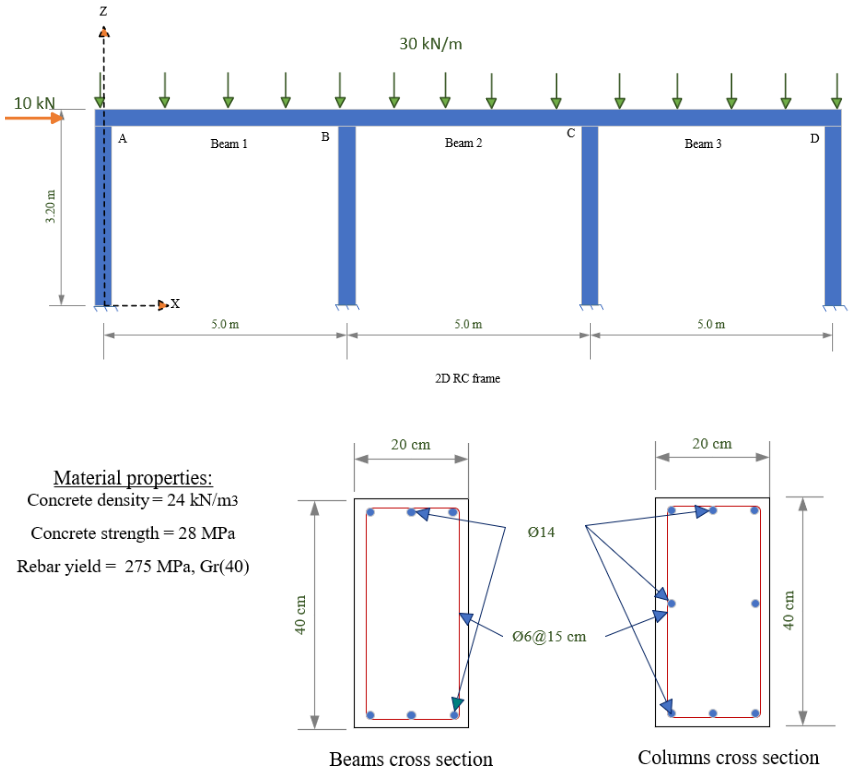

Figure 1. Reinforced concrete structural frame

The Zero value means no rigid zone, which is centerline to centerline [9]. This indicates that the element runs the full length from joint to joint. The One value means fully rigid. This means the element is shorter and that a rigid link connects the element to the joint. Where options in SAP 2000 can be used to model the rigidity by modifying the end length offset and panel zone options. Modelling the rigidity of the beam-column joint, first, centre to centre (0.0) which historically, is the most common and is the simplest modelling approach, the beam section is continued to the column centre. Second, use a 0.25 rigid end offset where a rigid link connects the end of the beam at the column face to the column centerline. And third, use 0.50 rigid end offset, and so on until reaches a value of 1, repeating the structural analysis each time and recording the resulting deformation on the elements for later comparison [10]. In this model, the vertical loads represent the self-weight of the structural elements and an applied load of 30 kN/m. Additionally, a concentrated lateral load of 10 kN is considered.

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Structural analysis is performed, and the resulting deformations are recorded for each degree of rigidity as indicated above.

Results

Table 1 presents the results of the structural analysis for the adopted cases of different rigidity levels. The results represent the maximum deformations occurring at joint A and beam 1. Figure 2 illustrates the relationship between the rigidity level and the deformation in the X-direction at joint A. Figure 3 shows the deformation of beam 1 about the Y-axis, which generates the design moment for the beam. Figure 4 presents the normalized deformation relationship for the maximum values to determine the optimal zone for the deformation values, where the optimal rigidity level is achieved. The negative sign has been omitted in the plotted relationship.

Table 1. Results of the structural analysis (Rigidity Level against Deflection)

Rigidity Level	Deflection								
	Gravity load only			Lateral load only			Both gravity and lateral loads		
	joint (A)		Mid span Beam 3	joint (A)		Mid span Beam 3	joint (A)		Mid span Beam 3
	Ux	Uz	Uz_{beam}	Ux	Uz	Uz_{beam}	Ux	Uz	Uz_{beam}
0	-0.068	-0.122	2.844	0.381	-0.002	-0.053	0.312	-0.123	2.189
0.25	-0.071		2.64	0.375			0.286	-0.123	2.16
0.50	-0.075		2.44	0.335			0.261	-0.124	2.42
0.75	-0.078		2.255	0.314			0.236	-0.124	2.234
1.0	-0.081		2.074	0.294			0.213	-0.124	2.053

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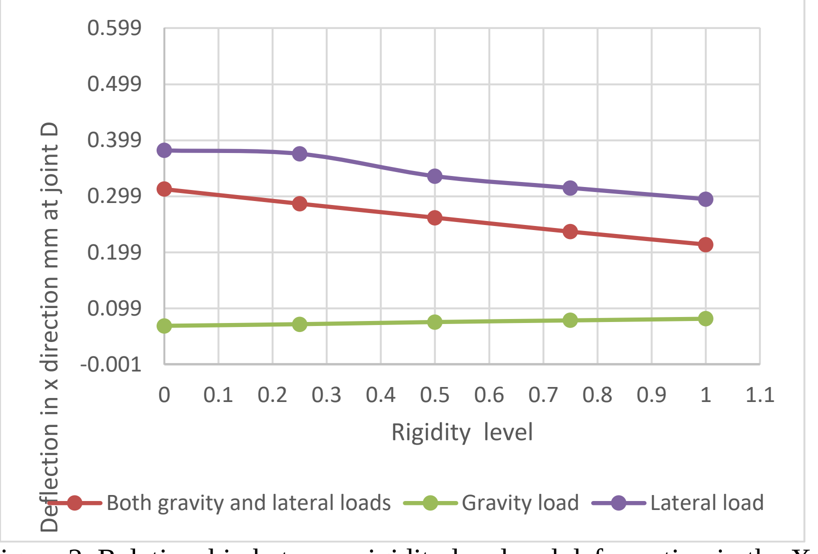

Figure 2. Relationship between rigidity level and deformation in the X-direction at joint D.

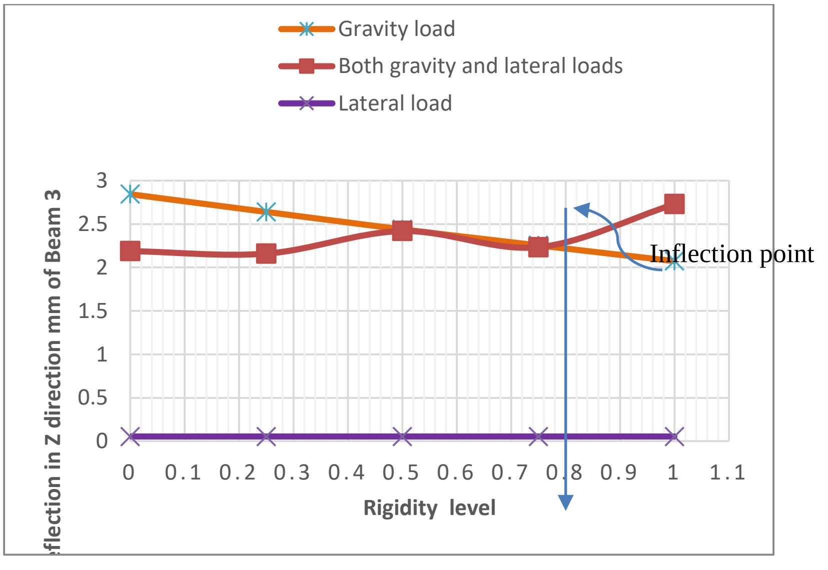

Figure 3. Deformation of beam 1 about the Y-axis beam 1

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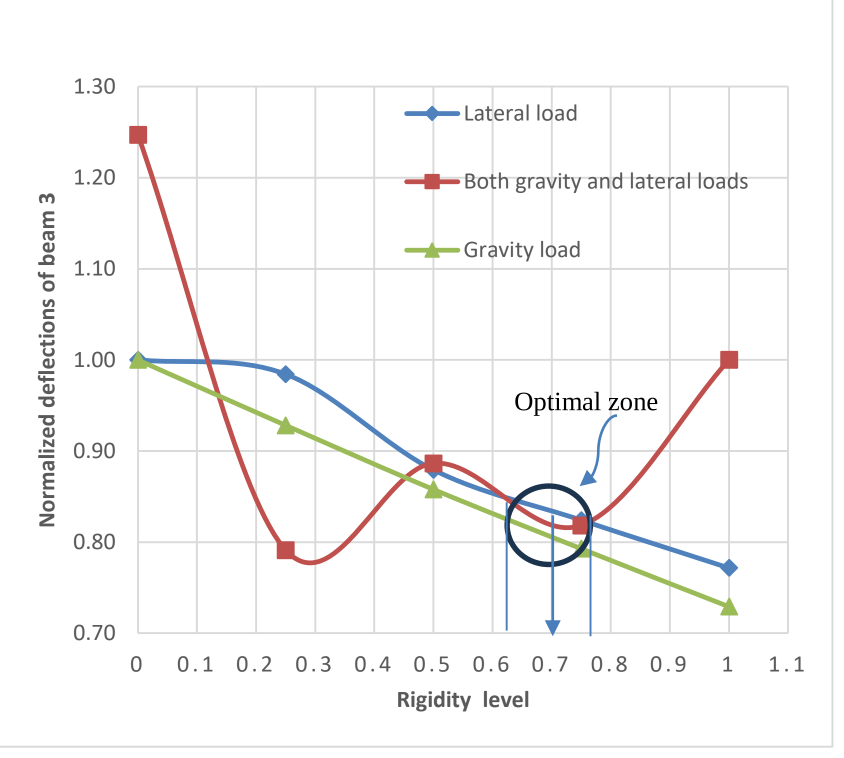

Figure 4. Normalized deformation relationship for the maximum values

Results discussion

Figure 2 illustrates that under vertical load-only, the deformation at joint D is relatively small because it is not in the direction of the applied load. As the stiffness increases, the deformation at joint D increases, which is expected since the joint stiffness approaches full restraint, meaning the rotational flexibility at the joint decreases. Consequently, the deformation at the mid-span of the beam, where the positive moment region is located, decreases, while it increases at the joint (negative moment region). This behavior is desirable because it results in a balanced reinforcement distribution at the mid-span (bottom reinforcement) and the joint (top reinforcement). On the other hand, the deformation due to lateral loading alone exhibits the highest values since it aligns with the direction of the applied load. This displacement decreases as the stiffness increases, which is also expected because the stiffness between the beam and the column increases at the joint. Meanwhile, the deformation resulting from the combined effect of vertical and lateral loads follows a behavior between the two cases, leaning more toward the

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deformation pattern of lateral load-only, which exhibits the largest deformation values.

Based on the fact that beam curvature governs its depth and design reinforcement ratio, Figure 2 shows that the deformation at the mid-span of Beam 1 decreases linearly with increasing stiffness under vertical loading. However, when the effect of lateral loading is introduced, a nonlinear and fluctuating behaviour is observed. Regardless of these fluctuations, the key aspect here is the inflection point, beyond which a significant difference in deformation values due to vertical and lateral loads begins to appear. This inflection point represents the convergence in behaviour, marking the ideal rigidity level, which is approximately 0.72.

Additionally, based on the principle of optimization, the deformation values at the mid-span of Beam 3 have been normalized against the maximum values, as shown in Figure 4. From this, can conclude that the ideal rigidity range (the optimal zone) lies between 0.64 and 0.76, with an average of 0.7.

Conclusion

This study examined the impact of beam-to-column connection rigidity on the structural performance of reinforced concrete (RC) frames in common residential buildings in the state of Libya. By considering various levels of connection rigidity, the research demonstrated that partial rigidity significantly influences deformation patterns. The SAP2000 structural analysis revealed that incorporating realistic connection rigidity can reduce beam deformation by up to 20%, leading to optimized member sizes and material savings.

A key finding of this study is that the ideal rigidity level for beam-to-column connections in single-story RC frames lies within the range of 0.64 to 0.76, with an optimal value of around 0.72. This balance ensures reduced material consumption while maintaining structural integrity and serviceability. Traditional design practices, which often assume either fully rigid or fully pinned connections, tend to overestimate required section sizes, resulting in unnecessary costs. However, the findings suggest that integrating partial rigidity into design considerations can enhance sustainability without compromising safety.

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From a practical perspective, common construction methods in the state of Libya inherently provide some degree of connection rigidity, yet this advantage is often overlooked in conventional design approaches. Recognizing and incorporating this factor into structural modelling can lead to more cost-effective and environmentally sustainable building solutions.

Finally, this study underscores the need to refine existing structural design methodologies by accounting for partial connection rigidity. The findings provide valuable insights for engineers aiming to optimize RC frame structures, offering a pathway toward more economical, efficient, and sustainable construction practices. Future research can extend this work by exploring the effects of connection rigidity on multi-story buildings and dynamic loading conditions, further enhancing structural optimization strategies..

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