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Seismic Design Optimization for Long-Span Warehouses: A Comparative Study of Ordinary and Intermediate Moment Resisting Frames

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Abstract This research addresses the seismic resilience of long-span steel warehouses, specifically focusing on the application of a moment-resisting frame system (MRFS). The main objective of this study is to comprehensively examine and compare the seismic performance of long-span warehouses using two distinct MRFS configurations: the ordinary moment-resisting frame system (OMRFS) and the intermediate moment-resisting frame system (IMRFS). The investigation strictly adhered to the Indonesian Building Code (SNI) guidelines. Notably, the results demonstrate striking similarities in the distribution of internal forces within the beams and columns for both the OMRFS and IMRFS systems in regions characterized by low to moderate seismic activity. This observation was primarily attributed to the predominant influence of gravitational loads under such conditions. This study reaffirms the appropriateness of the selected beam and column profiles for both systems, underlining the structural robustness of the designs. A key highlight of this investigation is the revelation of a substantial cost advantage associated with OMRFS endplate connections across a range of span configurations. These cost savings, when compared to IMRFS, indicate that the position of OMRFS is a cost-efficient choice, especially in regions with low to moderate seismic risk. These findings provide valuable guidance for stakeholders involved in the design and construction of long-span structures and offer a unique perspective that combines seismic resilience and cost-effectiveness.

Keywords Steel Structure, Long-Span Structure, Earthquake, Resisting Frames, Building System

1. Introduction

The construction industry employs steel and concrete structures with unique material properties and characteristics. Structural planning and design are critical for ensuring the safety and integrity of buildings [1], [2]. In this complex landscape, the integration of architecture becomes crucial, challenging architects to seamlessly weave seismic design elements into the aesthetic and functional fabrics of buildings. Architects play a pivotal role in spatial planning, material selection, and cultural sensitivity, ensuring that structures not only withstand seismic forces but also reflect cohesive architectural vision.

Long-span structures, such as steel warehouses, present a unique challenge. Although they are typically designed to withstand wind loads owing to their expansive surface area, they must also be fortified against seismic loads [3], [4]. This research focuses on the seismic resilience of long-span steel warehouses, emphasizing the application of a moment-resisting frame system (MRFS).

Steel structures stand apart from their concrete counterparts owing to their notable attributes. Notably, steel structures feature abbreviated construction schedules and originate from controlled manufacturing environments characterized by specialized equipment that ensures high-quality standards [5]–[7]. Nevertheless, these structures incur elevated construction expenses, necessitate skilled labour for assembly, and manifest susceptibility to fire hazards.

Steel structures designed for earthquake resistance exhibit adaptability to varying levels of seismic activity ranging from minor to severe tremors. These designs prioritize elasticity, allowing for energy absorption and dissipation through controlled deformation. The moment-resisting frame system (MRFS), which is categorized as an Ordinary Moment-Resisting Frame System (OMRFS), Intermediate Moment-Resisting Frame System (IMRFS), and Special Moment-Resisting Frame System (SMRFS), has demonstrated efficacy in countering lateral, axial, and moment loads induced by earthquakes [8]–[11].

A critical factor in seismic design is ductility, which pertains to the ability of a structure to deform without catastrophic failure during an earthquake. Ductility is a measure of the capacity of a structure to undergo plastic deformation while remaining within the acceptable safety limits [12]–[15]. This is a vital property because it allows a structure to absorb energy and dissipate seismic forces gradually, thereby enhancing its resilience during earthquakes. Figure 1 shows the ductility of moment-resisting frame systems.

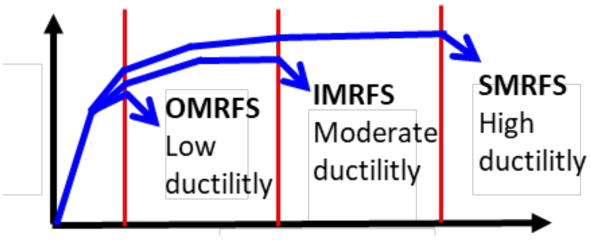

Figure 1. Moment resisting frame ductility

Moreover, in recent studies, the formation of fragility curves for steel building frames under earthquake ground motions has been a topic of substantial interest. These fragility curves provide valuable insights into the probability of failure of structures under various seismic intensities, and can serve as critical tools for assessing performance levels. The probability of failure, particularly in relation to the drift criterion exceeding specific performance levels, has become an essential consideration in fragility curve development [16].

In alignment with the Indonesian Building Code SNI 1726-2019 [17], either the ordinary moment-resisting frame system (OMRFS) or the intermediate moment-resisting frame system (IMRFS) may be employed, especially in regions characterized by low to moderate seismic activity. Careful consideration of specific system requirements is imperative during the design phase.

The selection between an ordinary moment-resisting frame system (OMRFS) and an intermediate moment-resisting frame system (IMRFS) has significant implications for structural design. The pivotal distinction between these systems lies in their capacity to withstand lateral forces, often quantified in terms of ductility, which is the capacity to deform without failure during an earthquake [12], [18], [19].

OMRFS is known for its rigidity but exhibits relatively limited ductility. It finds applications in structures exposed to lower seismic hazard levels, or in cases where cost constraints prevail. Conversely, an IMRFS is deployed in structures confronting higher seismic risks or those of elevated societal importance, such as hospitals and government buildings [20], [21].

While previous studies have addressed the design and application of steel structures using either the ordinary moment-resisting frame system (OMRFS) or the intermediate moment-resisting frame system (IMRFS) individually, there is a conspicuous research gap in systematically comparing the performance of both systems within diverse structural contexts and for various span configurations. The existing literature has largely focused on singular approaches to seismic design, often overlooking the critical decision-making process involved in selecting between two systems. This research aims to bridge this gap by providing a comprehensive comparison between the OMRFS and IMRFS, shedding light on their relative merits, particularly concerning long-span steel warehouse structures. By doing so, it seeks to enhance our understanding of the structural behaviour and cost efficiency of these systems, thus offering valuable insights for practitioners and stakeholders engaged in the design and construction of long-span steel buildings.

The research methodology encompasses the derivation of the internal forces within a structure through structural computer simulations. It further encompasses deflection calculations between levels and stability assessments, adhering to relevant design codes and standards. By providing a comprehensive design and calculations for long-span steel structures implementing both the OMRFS and IMRFS systems, this study provides valuable insights into the existing knowledge base.

2. Methodology

The primary objective of this study is to conduct an in-depth investigation of the behaviour and performance of long-span warehouses with a span of 30 m, as illustrated in Figure 2. In alignment with best practices in architectural design, this approach ensures a holistic investigation that not only delves into structural considerations, but also integrates architectural principles. This methodology is designed to converge with best practices in architecture, acknowledging the pivotal role of architectural considerations in shaping the behaviour and performance of the studied structures.

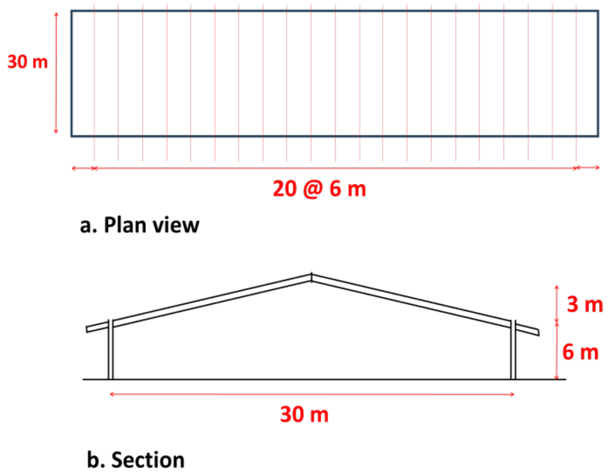

Figure 2. The selected frame in this study

The study location was selected based on the Indonesian Building Code (SNI) criteria, ensuring the permissibility of both the OMRFS and IMRFS. To assess the seismic performance of the structures, seismic parameters, such as design earthquake ground motion parameters, site classification, and soil profile, were determined based on SNI 1726-2019 [17]. The design earthquake ground motion parameters, including the peak ground acceleration and spectral acceleration, were calculated using the appropriate seismic hazard analysis procedures. The seismic parameters are listed in Table 1.

Table 1. Seismic parameters

Seismic parameter	OMRFS	IMRFS
Soil class	D	
Risk category	I	
Importance factor	1	
Ss	0.1756 g	
S1	0051 g	
R	3.5	4.5
Seismic coefficient	0.033	0.025
Base shear	48 kN	37 kN

The structural analysis and design in this research were based on the proficient use of the SAP2000 software package [22], as shown in Figure 3. This advanced tool has been widely embraced in civil engineering, empowering engineers and researchers to construct detailed and mathematically rigorous structural models. Moreover, it facilitates the application of diverse loading scenarios and the precise emulation of structural responses under various environmental conditions. The beams and columns were modelled using frame elements. However, the connection model is assumed to be rigid.

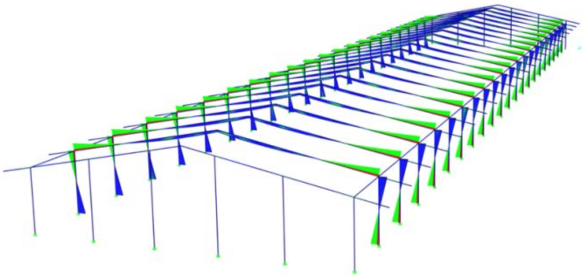

Figure 3. SAP2000 model

Indonesian Steel Design Code SNI 1729–2020 [23] was adopted for the design of the steel structure, including the connections. The design process includes the determination of the loads acting on the structure based on SNI 1727-2020 [24], selection of appropriate steel sections, and design of the connections between the structural elements.

3. Results and Discussions

3.1. Beam Design

Figure 4 presents the internal force diagram of the beam, as derived from SAP2000 software, for both the ordinary moment-resisting frame system (OMRFS) and the intermediate moment-resisting frame system (IMRFS). Notably, it is imperative to emphasize that while seismic forces differ between the OMRFS and IMRFS, internal forces exhibit remarkable similarities. This apparent congruence arises from a nuanced consideration: in the context of low to moderate seismicity levels, the seismic forces imparted on the structure are comparatively subdued when juxtaposed against the formidable gravitational loads inherent to long-span structures.

This observation is significant because it sheds light on the pivotal influence of seismicity levels in dictating the interplay between internal forces and structural responses. Specifically, in regions characterized by lower to moderate seismic activity, the pre-eminence of gravitational loads overshadows the seismic forces. Consequently, the internal forces within the beams of the OMRFS and IMRFS systems exhibit a discernible resemblance, which is primarily attributed to the prevailing dominance of the gravity-induced loading regimes.

Despite disparities in seismic forces, this convergence in internal forces underscores a critical facet of the structural design of long-span structures in seismic-prone areas. This underscores the dynamic interplay between seismic and gravitational forces, ultimately emphasizing the contextual significance of the seismicity levels in shaping the structural response. Consequently, these findings illuminate the nuanced intricacies of structural design considerations and offer valuable insights into the load-bearing characteristics of long-span structures under various seismic conditions.

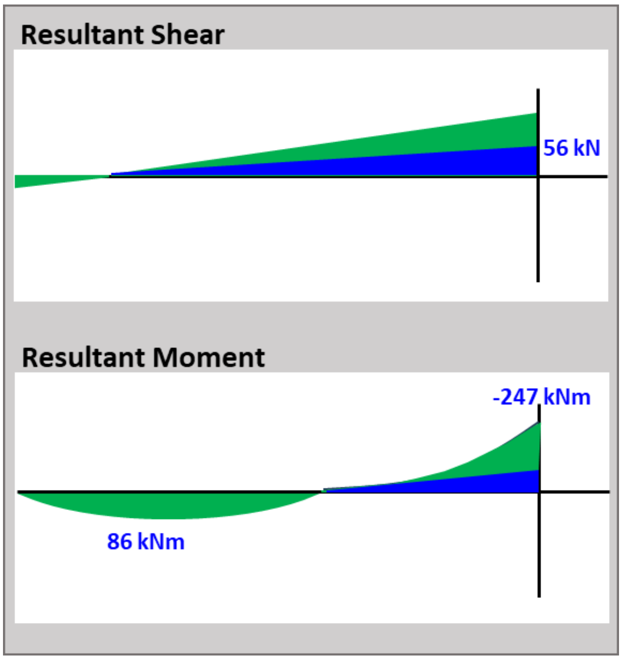

Figure 4. Internal force diagram of beam

The steel beam design for both the OMRFS and IMRFS systems was performed using SNI 1729:2020, as previously described. Table 2 summarizes the results of the design process. It can be seen that the IWF 400×200×8×13 mm beam profile, constructed from BJ37 steel, is a suitable choice for both OMRFS and IMRFS systems. The judicious selection of this beam profile ensures that it possesses the requisite load-bearing capacity to support structural elements safely under the influence of seismic loads.

Table 2. Beam design

	Symbol	Sytem	
		OMRFS	IMRFS
IWF Beam Profile	-	400×200×8×13	
Beam Moment Force	*Mu*	248 kNm	
Beam Moment Capacity	ϕMn	257 kNm	
Beam Shear Force	*Vu*	57 kN	
Beam Shear Capacity	ϕVn	461 kN	

3.2. Column Design

Similarly, the internal forces of the columns for the OMRFS and IMRFS exhibited similarities, as shown in Figure 5.

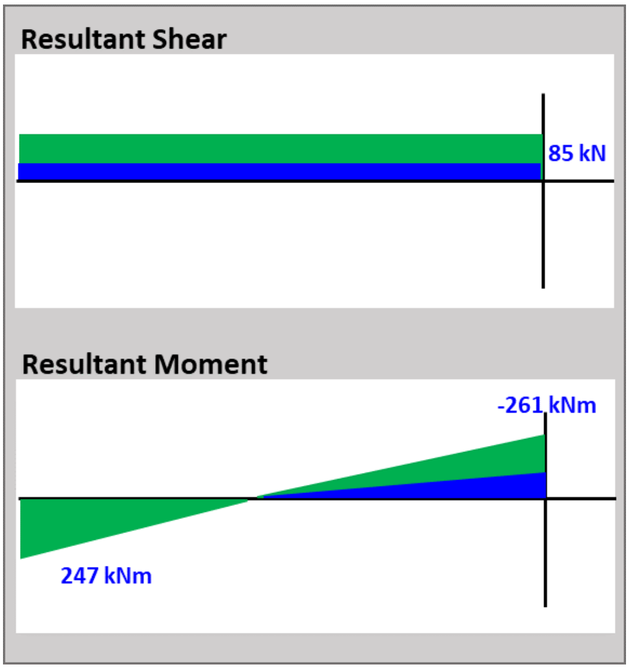

Figure 5. Internal force diagram of column

The steel column designs for both the OMRF and IMRF were performed in accordance with SNI 1729:2020. Table 3 summarizes the results of the design process.

Table 3. Beam design

	Symbol	System	
		OMRFS	IMRFS
IWF Column Profile	-	500×200×10×16	
Column Moment Force	*Mu*	262 kN	
Column Moment Capacity	ϕMn	412 kNm	
Column Axial Force	*Pu*	102 kN	
Column Axial Capacity	ϕPn	926 kN	
Column M-P Ratio	-	0,69 ≤ 1	

Based on the calculation results, it can be concluded that the IWF column profile 500×200×10×16 mm with BJ37 steel in both OMRF and IMRF systems can safely withstand the forces that occur on the structure, meeting the requirements of SNI 1729:2020. The calculated column moment capacities, axial capacities, and moment-axial ratios were all within the allowable limits.

It is important to note that the design of steel columns is crucial for the overall stability of a structure, particularly in seismic-prone areas. Therefore, the results of this design process provide essential information to ensure the safety and durability of warehouse structures under seismic loading conditions.

3.3. Connection Design

Table 4 summarises the connection design. The use of M27 bolts and 30 mm thick end plates is considered safe for both systems, as they meet the required bolt diameter and end-plate thickness according to the standards. However, it is interesting to note that the thicknesses of the stiffener plates used is 36 mm for OMRF and 38 mm for IMRF, and the thickness of the doubler plate per side is 6 mm for OMRF and 7 mm for IMRF. This suggests that the IMRF may have a slightly higher load capacity than the OMRF because thicker stiffener and doubler plates provide additional support.

Table 4. Connection design

	Symbol	Value	
		OMRFS	**IMRFS**
Connection Type	-	4E	
Shear Force	V_u	117 kN	119 kN
Moment Force	M_u	471 kN	495 kN
End Plate Width	b_p	225 mm	
Distance Between Bolts	g	105 mm	
Outer Bolt Vertical Distance	p_{fo}	40 mm	
Inner Bolt Vertical Distance	p_{fi}	40 mm	
Outer Bolt to End Plate Edge Distance	d_e	60 mm	
End Plate Height	d_p	600 mm	
Bolt Diameter Required	Db_{req}	25,7 mm	26,3 mm
Bolt Diameter Used	Db	27 mm (M27)	
Bolt Hole Diameter	D_{hole}	30 mm	
End Plate Thickness Required	$t_{p\ req}$	28,1 mm	
End Plate Thickness	t_p	30 mm	
Continuous Plate Stiffener Thickness	t_s	36 mm	39 mm
Doubler Plate Thickness Required	$t_{pg\ req}$	11,4 mm	12,9 mm
Doubler Plate Thickness Used	t_{pg}	12 mm	14 mm
Doubler Plate Thickness per Side	t_{pg} *per side*	6 mm	7 mm

3.4. Price Comparison at Various Span

A comprehensive comparative analysis of the various structural elements was performed. Table 5 meticulously details the price disparities for steel beams, Table 6 provides the financial distinctions concerning steel columns, and Table 7 captures the nuances in pricing related to end-plate connections. These tables provide invaluable insights into the economic implications associated with the selection of either the ordinary moment-resisting frame system (OMRFS) or the intermediate moment-resisting frame system (IMRFS) across varying span configurations.

An intriguing observation arises from the juxtaposition of data in Tables 5 and 6. It emerges that for the design of both beams and columns for the expansive long-span structure of a warehouse, there are no perceptible disparities in either weight or cost between the OMRFS and IMRFS systems across the entire spectrum of span variations. This intriguing parity underscores the economic neutrality of the two moment-resisting frame systems in the context of this specific structural configuration, regardless of span length.

Table 5. Comparison of OMRF and IMRF Steel Beam at Various Spans

	Span	Profile / Size	
		OMRFS	**IMRFS**
IWF Beam Profile	20 m	350×175×7×11 mm	
	30 m	400×200×8×13 mm	
	40 m	500×200×10×16 mm	
Total Beam Weight	20 m	23386 kg	
	30 m	46299 kg	
	40 m	83462 kg	
Total Price (Rp 16.500/kg)	20 m	Rp 385.875.600	
	30 m	Rp763.933.500	
	40 m	Rp 1.377.129.600	

Table 6. Comparison of OMRF and IMRF Steel Column at Various Spans

	Span	Profile / Size	
		OMRFS	**IMRFS**
IWF Column Profile	20 m	350×175×7×11 mm	
	30 m	450×200×9×14 mm	
	40 m	600×300×12×20 mm	
Total Column Weight	20 m	16070 kg	
	30 m	24624 kg	
	40 m	48924 kg	
Total Price (Rp 16.500/kg)	20 m	Rp 265.161.600	
	30 m	Rp 406.296.000	
	40 m	Rp 807.246.000	

Table 7. Comparison of OMRF and IMRF Steel Connection at Various Spans

Name	Span	Profile / Size	
		OMRFS	**IMRFS**
End Plate Thickness	20 m	28 mm	
	30 m	30 mm	
	40 m	32 mm	
Continuous Plate Thickness	20 m	30 mm	32 mm
	30 m	36 mm	39 mm
	40 m	29 mm	31 mm
Doubler Plate Thickness	20 m	16 mm	18 mm
	30 m		
	40 m	10 mm	12 mm
Total Connection Weight	20 m	3781 kg	3969 kg
	30 m	5873 kg	6150 kg
	40 m	8210 kg	8752 kg
Bolt Diameter	20 m	24 mm (M24)	
	30 m	27 mm (M27)	
	40 m	30 mm (M30)	
Bolt Price per Unit	20 m	Rp 50.000 (M24)	
	30 m	Rp 80.000 (M27)	
	40 m	Rp 110.000 (M30)	
Total Price (Rp16.500 /kg)	20 m	Rp 87.182.597	Rp 90.290.741
	30 m	Rp 136.592.677	Rp 141.160.904
	40 m	Rp 190.030.881	Rp 198.971.132

However, a discernible distinction materializes when we focus on the pricing dynamics shown in Table 7. This result meticulously delineates the weight and cost variances between the end-plate connections for the OMRFS and IMRFS, across various span configurations.

Specifically, Table 7 provides a cogent insight: the weight and cost of the end-plate connections in the OMRFS system consistently emerged as more economical when juxtaposed against their IMRFS counterparts across all span variations. The extent of this cost efficiency is manifested in the numbers: OMRFS boasts a price reduction of 3.4% for a 20-meter span, 3.2% for a 30-meter span, and 4.5% for a 40-meter span when compared to IMRFS within each respective span category.

Based on this compelling price comparison, it becomes evident that the ordinary moment-resisting frame system (OMRFS) unequivocally stands out as the more cost-efficient option for the selected structural configuration, as shown in Table 8. This finding holds significant implications for cost-conscious projects where optimizing construction expenses is a pivotal consideration.

Table 8. Comparison of OMRF and IMRF Steel Price at Various Spans

Span	Profile / Size	
	OMRFS	**IMRFS**
20 m	Rp 738.219.797	Rp 741.327.941
30 m	Rp 1.306.822.177	Rp 1.311.390.404
40 m	Rp 2.374.406.481	Rp 2.383.346.732

4. Conclusions

This comprehensive research endeavour delved into the seismic design and structural performance of long-span warehouses under the influence of seismic loads, with particular emphasis on the application of both the ordinary moment-resisting frame system (OMRFS) and intermediate moment-resisting frame system (IMRFS). The investigation encompassed various aspects of structural analysis, design, and economic evaluation, culminating in a nuanced understanding of the structural response and cost implications associated with these two moment-resisting frame systems.

The results of the structural analysis revealed a noteworthy similarity in the internal forces within the beams and columns of both OMRFS and IMRFS systems. This phenomenon stems from the predominant influence of gravitational loads in regions characterized by low to moderate seismicity, underscoring the contextual significance of seismicity levels in shaping structural responses.

The steel beam and column design, meticulously executed in accordance with the SNI 1729:2020 standards, revealed the suitability of the selected IWF beam and column profiles constructed from BJ37 steel for both OMRFS and IMRFS systems. These profiles exhibited the requisite load-bearing capacity to withstand the formidable forces induced by seismic events effectively, thereby ensuring structural integrity and resilience.

Furthermore, the connection design analysis reaffirmed the safety of employing M27 bolts and 30 mm thick end plates for both the OMRFS and IMRFS systems. Notably, the slightly thicker stiffener and doubler plates in the IMRFS system indicate a potentially higher load capacity, suggesting versatility in structural applications.

The economic evaluation, conducted across varying span configurations, yielded an intriguing finding: while there were no perceptible disparities in weight or cost for beams and columns between the OMRFS and IMRFS systems, a notable cost efficiency was discerned in favour of the OMRFS system concerning end plate connections. This cost advantage translated into a price reduction of 3.4% for a 20-meter span, 3.2% for a 30-meter span, and 4.5% for a 40-meter span when compared to IMRFS.

In conclusion, this study underscores the critical interplay among structural performance, seismicity levels, and economic considerations in the design of long-span warehouses. The findings suggest that the ordinary moment-resisting frame system (OMRFS) is a cost-efficient and structurally robust choice for such applications, especially in regions characterized by low to moderate seismic activity. Importantly, these findings extend beyond the realm of structural engineering and have significant implications for architectural practices. Architects can leverage these insights to inform their design decisions and select systems that not only ensure structural integrity, but also align with economic considerations. Thus, the study's outcomes provide architects with valuable information on optimal design choices, facilitating the creation of long-span warehouses that are not only resilient but also economically and architecturally sound.

Although this research provides valuable insights, it is essential to acknowledge certain limitations that guide future investigations in this domain. Future research should explore the application of the OMRFS and IMRFS in high-seismicity areas, consider a broader range of cost factors, and examine alternative connection types. Promising directions for future research include multi-system comparisons, particularly Special Moment-Resisting Frame Systems, the analysis of multi-story structures, investigations in higher seismic intensity regions, and comprehensive life-cycle cost analyses. These approaches will contribute to a more robust understanding of the seismic design and cost efficiency of long-span structures, thereby ensuring that engineering practices align with the evolving demands of seismic resilience and economics.

Acknowledgements

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