SEISMIC EVALUATION OF BUILDING FRAMES USING HIGH-PERFORMANCE STEEL

BY

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SYNOPSIS

The need for reliable seismic resistant structures is indispensable for earthquake prone area such as Indonesia. This paper presents a result of joint research project between Japanese Society of Steel Construction, Japan Iron and Steel Federation, and Indonesian Society of Steel Construction; to evaluate the seismic performance of a 4-story office building in Indonesia.

Two identical building frames with Special Moment Frames on its perimeter were designed using widely used SS400 steel and high-performance SN490B steel according to the Indonesian Seismic Provisions for Structural Steel Buildings which is adopted from US Codes. The seismic criteria for both frames were applied, i.e. ductile material, highly ductile member, inter-story drift, building irregularity, and capacity design (strong-column weak beam), as well as the seismic building parameters. The design shows the advantage of the SN frame in steel weight due to its higher yield stress and lower Ry, although it could not be fully attained since the design of this building is governed by the drift, not by the strength.

Furthermore, the result of the non-linear static push over analysis of both design frames shows that the SN frame shows: (1) less frame stiffness; (2) higher frame strength; (3) more ductile frame; (4) better energy dissipation; and (5) better plastic hinge formation that prevents a sudden collapse due to column failure.

From the viewpoint of risk assessment for building due to earthquake occurrence, the use of SN490B steel with a smaller variation of Yield Point ensures the structure will perform much closer to the design performance that was determined for the building. This indeed will increase the performance of the building in protecting the human live and social assets.

Keywords: seismic performance, high-performance steel, plastic hinge formation

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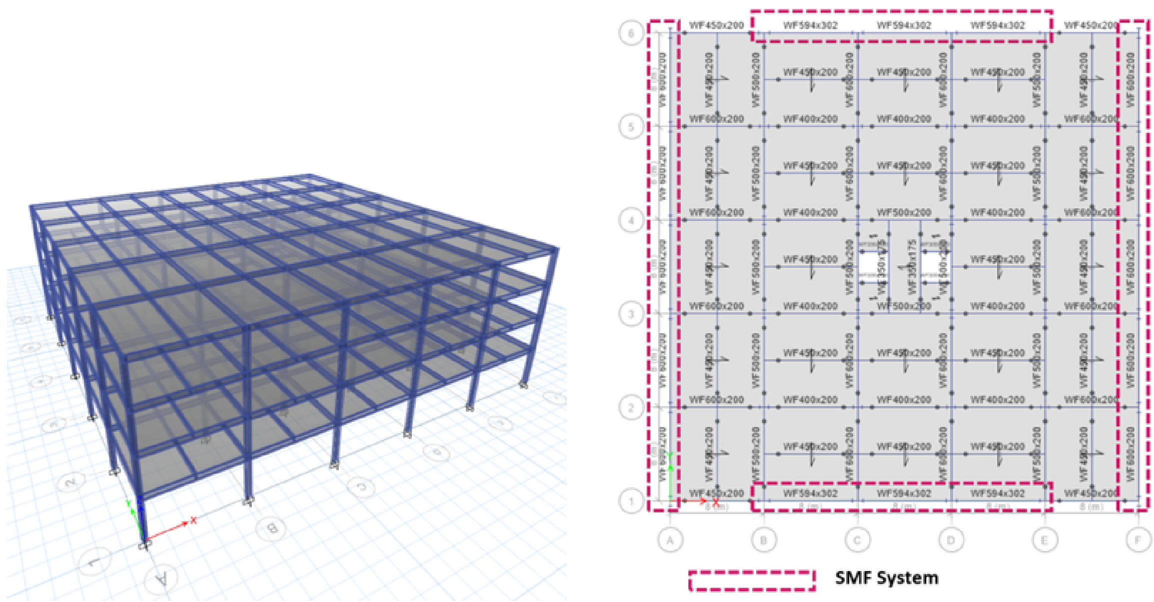
Introduction

The need for reliable seismic resistant structures is indispensable for earthquake prone area such as Indonesia. The Indonesian seismic resistant building codes have been updated since 2002, including the seismic provisions for structural steel buildings. The recent codes are the adoption of some U.S. building codes, i.e. Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE 7-16), Specification for Structural Steel Buildings (AISC 360-10), and Seismic Provisions for Structural Steel Buildings (AISC 341-10). The codes will be updated following the future revision of the U.S. building codes.

In addition to the code compliance, the need for a higher performance steel material is also essential to secure the performance of seismic resistant structure as stated in recent Codes. This paper presents a result of joint research project between Japanese Society of Steel Construction, Japan Iron and Steel Federation, and Indonesian Society of Steel Construction; to evaluate the seismic performance of structural steel building design using the SN490B steel as compared to the SS400 steel that is more commonly used in Indonesia so far.

Materials and Method

A study has been conducted to evaluate the use of SN490B in the design of four-story office building according to the recent Indonesian Steel Seismic Building Codes (SNI 1726:2019 [3] and SNI 7860:2015 [5]). The building is located on a soft-soil at Bandung, West-Java. Two identical structural frames were analyzed, using SN490B steel and commonly used SS400 steel, respectively. The frame model and data of the buildings are shown in Figure 1 and Table 1. The building seismic design parameters are determined based on the Indonesian Seismic Loading Code [3] and is shown in Table 2.



a. 3D model b. Typical Plan

Figure 1 Structural model of 4-story Office Building

Preliminary design was proposed for both frame models using the Wide-flange sections. The structural analysis for the Seismic Loading Combination, i.e. 1.2 Dead Load + 1.0 Live Load + 1.0 Earthquake, governed the design of beam elements.

Table 1 Data of Steel Building

Dimension	Typical 4-story (40 m x 40 m, 5 x 8 m in each direction)		
Steel Materials		SS400	SN490
	Yield stress, Fy, MPa	235	325
	Tensile strength, Fu, MPa	400	490
Sectional member	Wide flange		
Seismic Resisting System	Special Moment Frames on building perimeter		
Gravity Resisting System	Gravity Frames on building interior		
Building Irregularity	No (vertical and horizontal)		
Building Standards	SNI 1726:2019, SNI 1729:2015, SNI 7860:2015, equivalent to ASCE 7-16 (seismic part), AISC 360-10, AISC 341-10.		

Table 2 Seismic Design Parameter

Risk Category	II
Importance Factor	1.0
SDs	0.6987 g
SD_1	0.6415 g
Seismic Design Category	D
Response Modification Coefficient, R	8
Overstrength Factor, Ωo	3
Deflection Amplification Factor, Cd	5.5
Redundancy Factor, ρ	1.0
Drift Limit	2.5 %

The capacity design was conducted to determine the dimension of columns that are parts of Special Moment Frames according to the Seismic Provisions for Structural Steel Buildings [5]. Since the provision only specifies the Ry value (= expected Yield Stress/ specified Yield Stress) for ASTM steels, the design assumed the Ry = 1.5 for SS400 and Ry = 1.338 for SN490B, which corresponds to the Ry values for ASTM A36 and data from AIJ [2]. This Ry value is critical in the design stage as well as in the analysis of seismic performance.

A non-linear static push over analysis was conducted to evaluate the seismic performance of the two frames (namely SS frame and SN frame) using the backbone of plastic hinge model as shown in Figure 2. This backbone model and the values of its parameters are defined for both SS400 and SN490N beams and columns according to ASCE 41-17 [1], Section 9.4 : Steel Moment Frames. The performance of structure was also determined according to acceptance criteria stated in Section 7.6: Alternate Modeling Parameters and Acceptance Criteria. Figure 3 shows the illustration of acceptance criteria that includes Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

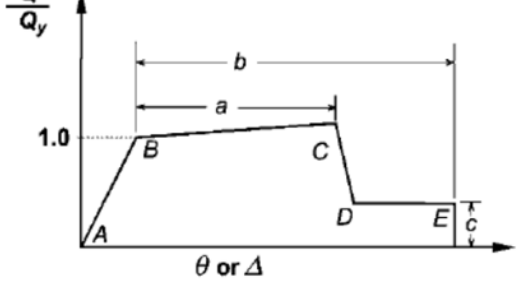


Figure 2 Plastic Hinge Model [1]

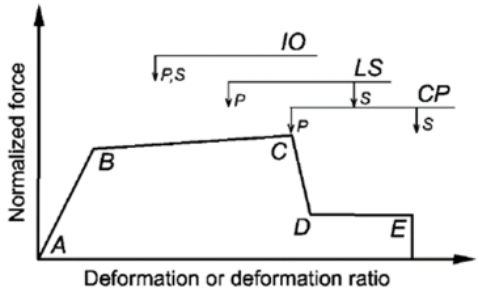
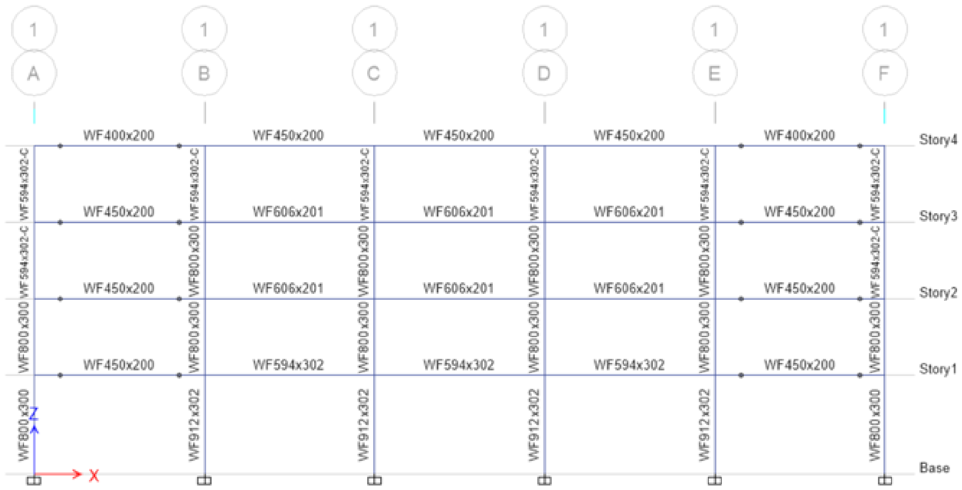


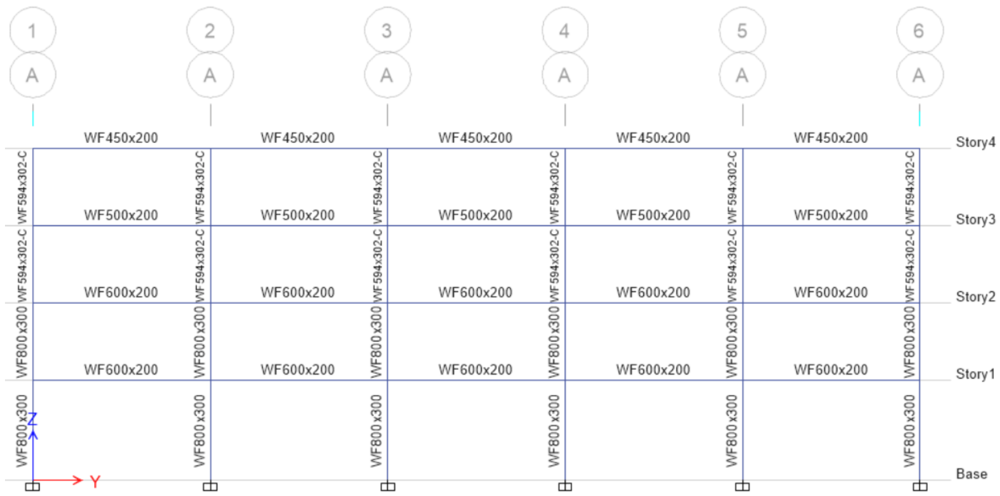
Figure 3 Acceptance Criteria Illustration [1]

Results

The design for the two buildings is shown in Figure 4 and Figure 5. It showed that the SN frame provided smaller sections of beams and columns due to its higher yield stress (1.3 times higher than yield stress of the SS400) and lower Ry values (to obtain less required column strength in capacity design), but eventually resulted in higher inter-story drift than the SS frame. The seismic requirement for the drift limit of 2,5% requires heavier column sections so that the DCR for Special Moment Frame of SN steel could not be maximized..

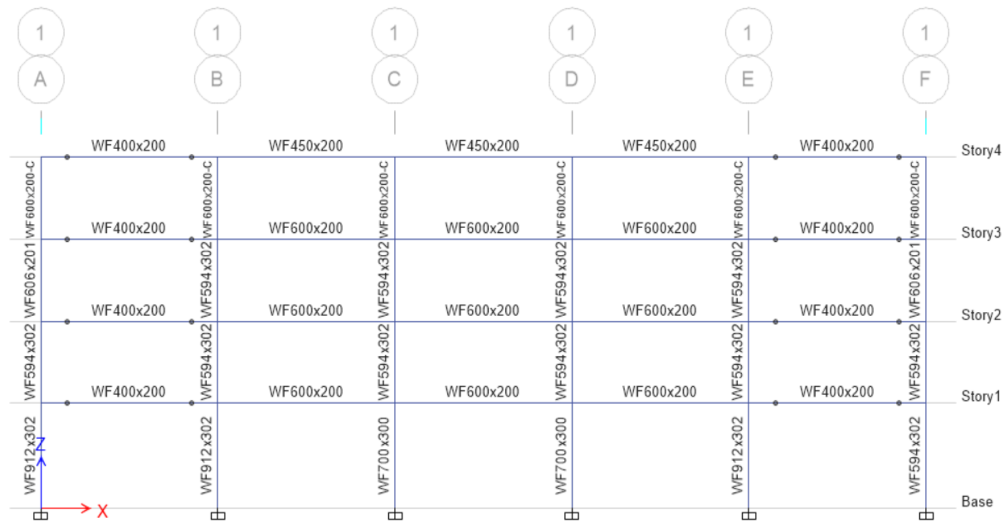


(a) X-direction

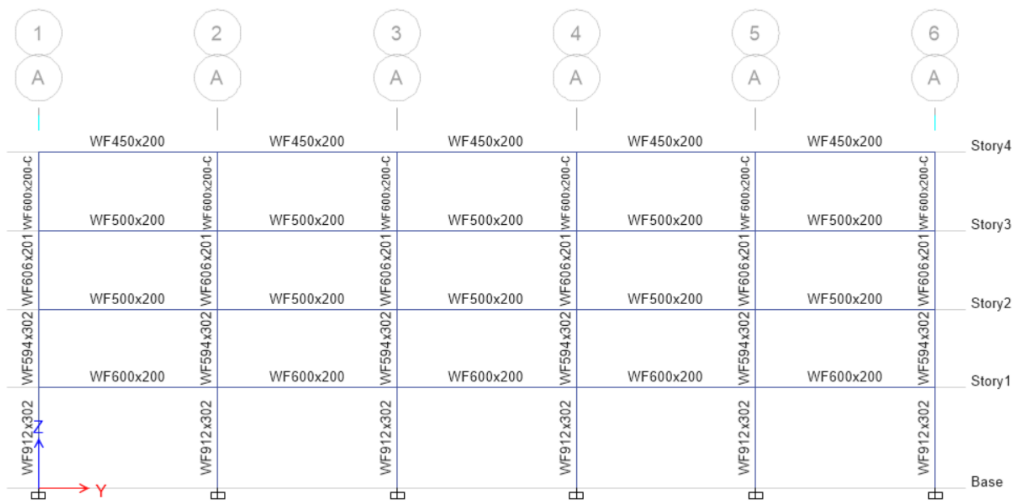


(b) Y – direction

Figure 4 Special Moment Frame – SS400



(a) X – direction



(b) Y – direction

Figure 5 Special Moment Frame – SN490B

Table 3 and 4 show the Demand-Capacity Ratio (DCR) of Special Moment Frames and Gravity Frames, respectively. Due to the requirement for Highly Ductile Member, the use of available beam sections in Special Moment Frames will result in less DCR than beam in Gravity Frames, for both SS and SN frames. The DCR for the Gravity Frames can be maximized since its columns are leaning columns and not part of lateral force resisting system.

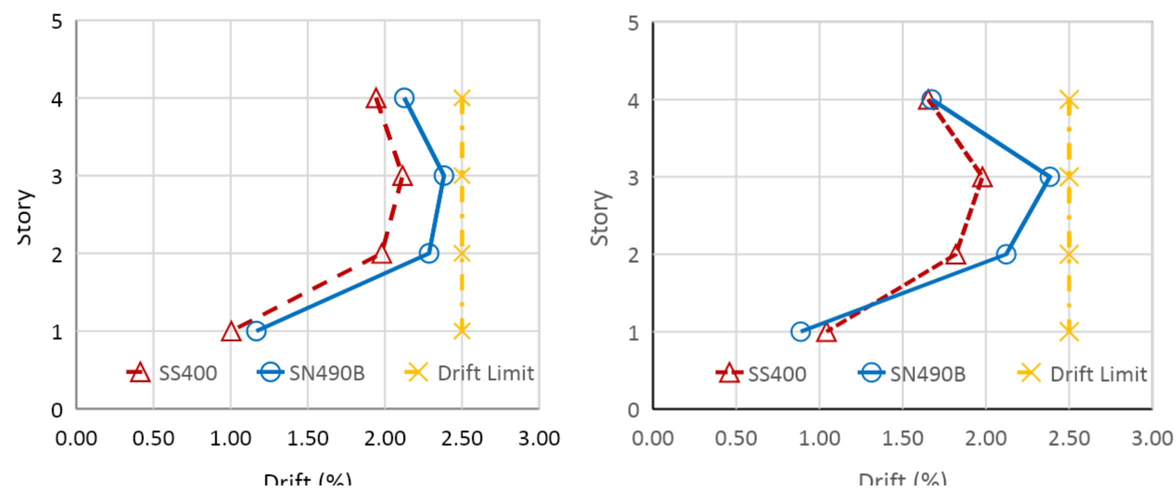
Table 3 DCR for Special Moment Frames

Story	Element	SS400		SN490B	
4F	Column	WF500x200	0.198	WF500x200	0.153
	Beam	WF400x200	0.788	WF350x175	0.878
	Beam	WF450x200	0.843	WF400x200	0.776
3F	Column	WF588x300	0.294	WF600x200	0.394
	Beam	WF400x200	0.954	WF400x200	0.801
	Beam	WF450x200	0.865	WF450x200	0.846
	Beam	WF500x200	0.910	WF500x200	0.888
	Beam	WF600x200	0.902		
2F	Column	WF588x300	0.510	WF588x300	0.384
	Beam	WF400x200	0.954	WF400x200	0.801
	Beam	WF450x200	0.865	WF450x200	0.846
	Beam	WF500x200	0.910	WF500x200	0.888
	Beam	WF600x200	0.902		
1F	Column	WF700x300	0.821	WF588x300	0.738
	Beam	WF400x200	0.954	WF400x200	0.819
	Beam	WF450x200	0.882	WF450x200	0.846
	Beam	WF500x200	0.910	WF500x200	0.888
	Beam	WF600x200	0.902		

Table 4 DCR for Gravity Frames

Story	Element	SS400		SN490B	
4F	Column	WF500x200	0.197	WF500x200	0.152
	Beam	WF400x200	0.788	WF350x175	0.878
	Beam	WF450x200	0.843	WF400x200	0.776
3F	Column	WF588x300	0.293	WF600x200	0.394
	Beam	WF400x200	0.954	WF400x200	0.801
	Beam	WF450x200	0.865	WF450x200	0.846
	Beam	WF500x200	0.910	WF500x200	0.888
	Beam	WF600x200	0.902		
2F	Column	WF588x300	0.509	WF588x300	0.399
	Beam	WF400x200	0.954	WF400x200	0.801
	Beam	WF450x200	0.865	WF450x200	0.846
	Beam	WF500x200	0.91	WF500x200	0.888
	Beam	WF600x200	0.902		
1F	Column	WF700x300	0.811	WF588x300	0.686
	Beam	WF400x200	0.954	WF400x200	0.819
	Beam	WF450x200	0.882	WF450x200	0.846
	Beam	WF500x200	0.91	WF500x200	0.888
	Beam	WF600x200	0.902		

Figure 6 shows the inter-story drift of both frames. The drift requirement eventually prevents to maximize the DCR of Special Moment Frames. In other words, the advantages of using SN490B steel will be more evident for building design which is not governed by the drift limit.



(a) SS400 (b) SN490B

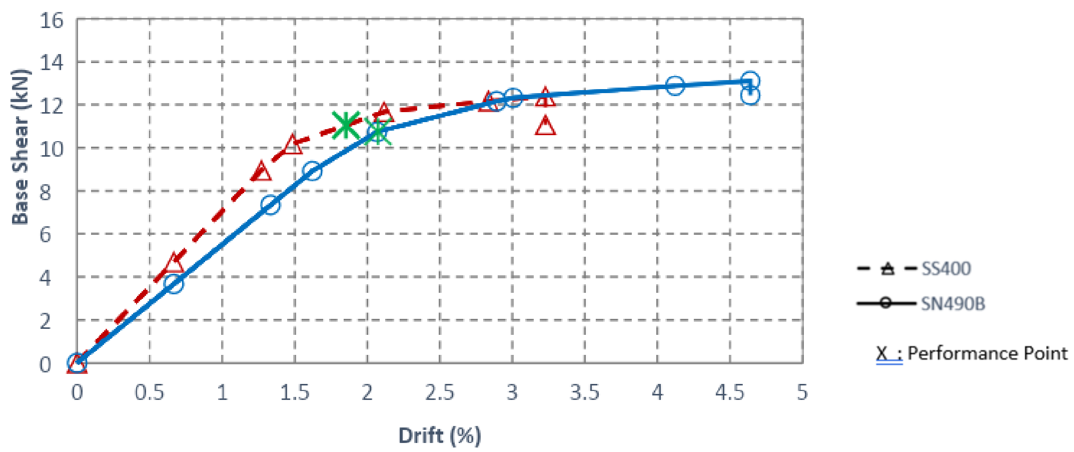
Figure 6 Interstory drift

The design for the two frames shows that the SN frame provides 12.81% less weight of columns and beams than the SS frame (Table 5). This number is expected to be higher for building with more effective lateral displacement resisting system (e.g. braced frames, dual system with shear wall), since the design will be governed by the strength, not by the drift limit, so that the DCR of structural members (e.q. beam, column, bracing) could be maximized.

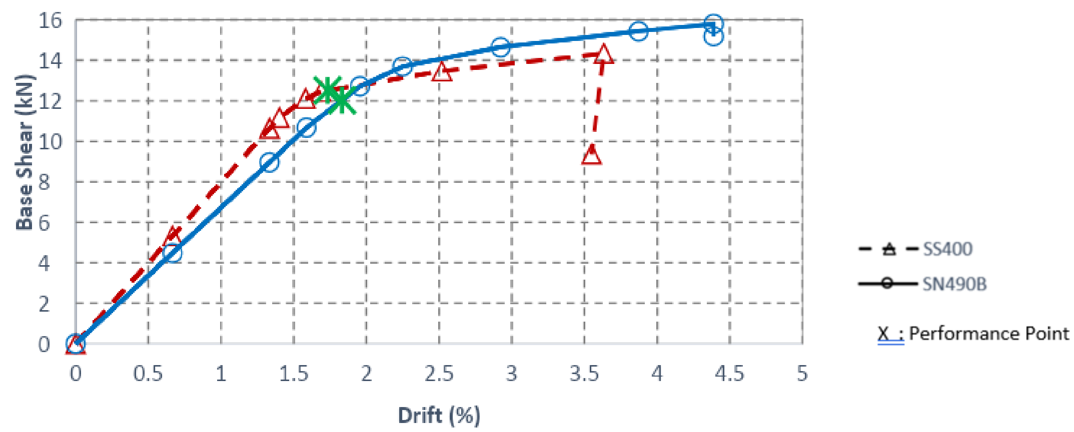
Table 5 Structural Steel Weight

Element	Weight (kg)	
	SS400	**SN490B**
Column	95,726	82,061
Beam	171,962	149,747
Sub-Beam	57,251	51,491
T o t a l	324,939	283,299
Deviation		41,639 (12.81%)

The results of push over analysis for the two Special Moment Frames are shown in Figures 7(a) and (b).



(a) X – direction



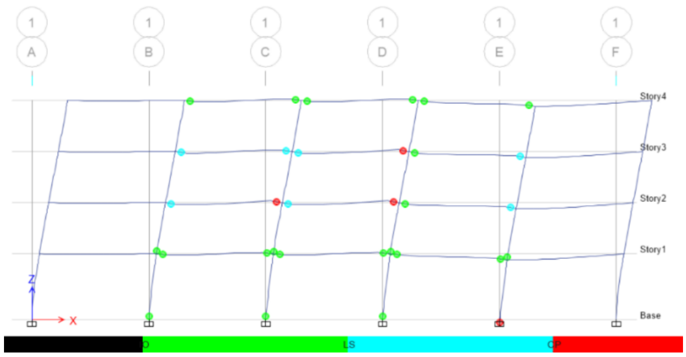
(b) Y – direction

Figure 7 Push over for SS Frame and SN Frame

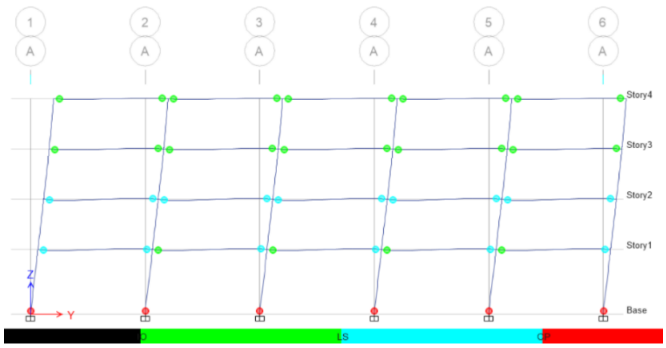
Discussion

The result of push-over analysis in Figure 7(a) and (b) shows the good performance of SN frame in addition to its advantage in steel weight, as compared to SS frame. The higher overstrength as well as the higher ductility of SN frame in X-direction and Y-direction are supported by a good plastic hinge formation. Figure 8 and 9 show the plastic hinges formation at the final step in SS frame and SN frame, respectively. The red dot indicates the strength loss on the elements (represented by point D in the plastic hinge model in Figure 2). The strength loss on beam elements is identified in SN frames, and not on column elements as in SS frame. The use of stronger column of a slightly heavier section in the SN frame is expected to prevent building collapse by still maintaining the less structural weight than the SS frame.

Furthermore, the good plastic hinge formation results in a higher capacity of dissipated energy (Figure 10), which indicates a better seismic performance. The good performance of SN frame could be further improved i.e. by the use of larger sections, which leads to less DCR and slightly heavier structure, but still provides a considerably lighter structure than the SS frame.

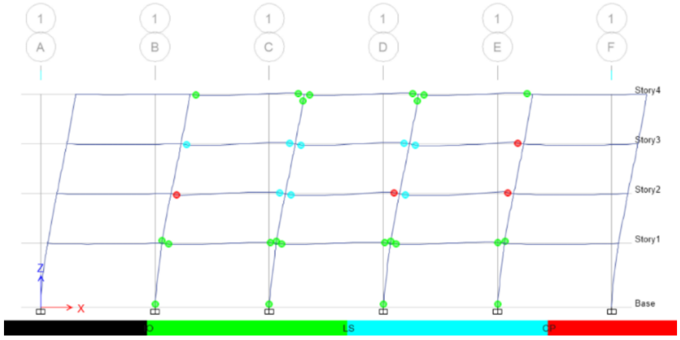


(a) X - direction

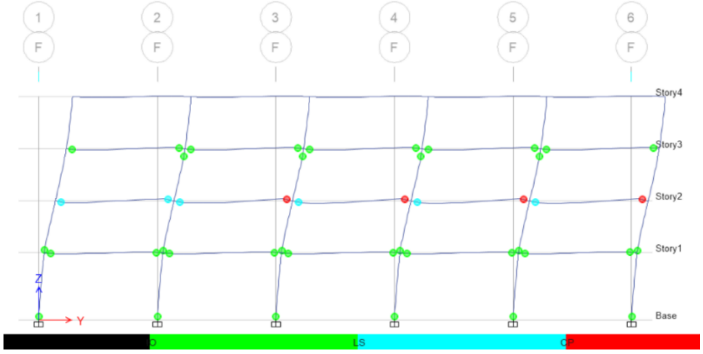


(b) Y – direction

Figure 8 Plastic hinge formation at the final loading step for SS Frame

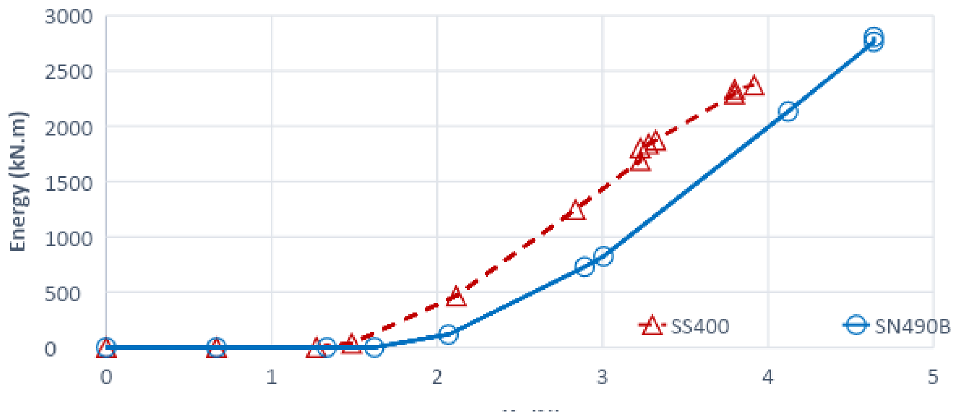


(a) X – direction

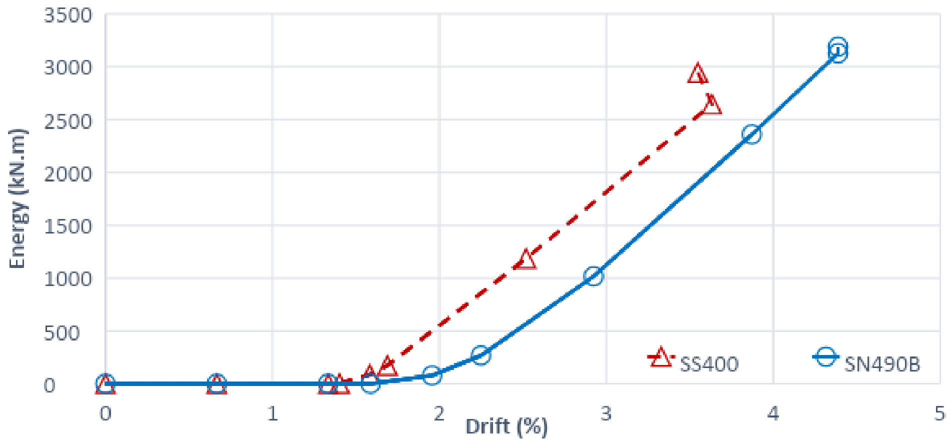


(b) Y – direction

Figure 9 Plastic hinge formation at the final loading step for SN Frame



(a) X – direction



(b) Y – direction

Figure 10 Dissipated Energy of SS Frame and SN Frame

Table 6 shows the seismic performance of both frames based on the performance points of the push over analysis shown in Figure 7(a) and (b). The seismic performance of SN frame in X-direction is Immediate Occupancy, which is better than Life Safety for SS frame.

Table 6 Performance of SS and SN Frames

Push-over Direction	Frame	First Yield (kN)	Performance Point		Limit Displacement (mm)			Building Performance
			Displacement (mm)	Base Shear (kN)	Immediate Occupancy	Life Safety	Collapse Prevention	
X	SS400	8,951	**278.04**	11,053	242.07	363.11	484.15	**Life Safety**
	SN490B	8,916	311.02	10,749	348.19	522.28	696.37	Immediate Occupancy
Y	SS400	11,168	260.04	12,507	272.45	408.68	544.91	Immediate Occupancy
	SN490B	10,512	274.90	12,032	330.22	495.34	660.45	Immediate Occupancy

More advantages of using SN490B steel in a seismic building design are expected by considering the followings: (1) limitation of upper yield stress to ensure the final collapse mechanism of frames as it assumed at design stage; (2) restrict yield ratio (yield stress to tensile strength) to 0.80 or lower, to provide better over-strength capacity; (3) limitation of fracture toughness index higher than 27 Joule at 0ºC to provide better weldability for better performance of connection; (4) limits the carbon, phosphorus, sulphur, and specified weld cracking sensitivity composition, to secure the weldability, workability and resistance to through-thickness cracking.

Conclusion

1. Design of two identical buildings (using SS400 steel and SN490B steel) with Special Moment Frames has been provided according to the recent Indonesia Seismic Building Codes. The design shows the advantage of the SN frame in steel weight due to its higher yield stress and lower Ry value. This advantage could be more apparent when the design of building structure is governed by the strength limit, not by the drift limit.
2. The result of the non-linear static push over analysis of both design frames shows that the SN frame exhibits: (1) less structural stiffness; (2) higher structural strength; (3) more ductile structure; (4) better structural performance; (5) better energy dissipation capacity; and (6) better plastic hinge formation that prevents a sudden collapse due to column failure.
3. From the viewpoint of risk assessment for building due to earthquake occurrence, the use of SN490B steel with a smaller variation of Yield Point ensures the structure will perform much closer to the design performance that was determined for the building. This indeed will increase the performance of the building in protecting the human live and social assets.

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