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The Effect of Steel Over Strength Ratio on Structure Behavior

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Abstract: Seismic design of steel building structures according to SNI 7860:2020 determining the necessary strength of structural members based on the expected yield stress, Ry.Fy, and the expected tensile stress, Rt.Fu. However, the values of Ry and Rt in SNI 7860:2020 are not yet based on the testing of steel products in Indonesia and are still based on the provisions in AISC 341-16. This research was conducted by collecting data on steel tensile test results to obtain the over-strength ratio and then modeling the steel frame building using the over-strength steel provisions of SNI 7860:2020 and based on the tensile test results to determine the difference in structural behavior. Based on the tensile test results, WF300 steel has a yield strength ratio (Ry) of 1.78, which is higher than the SNI specification of 1.5, and a tensile strength ratio (Rt) of 1.35, which is higher than the SNI specification of 1.2. Based on pushover analysis, the deviation value at the initial formation of the plastic hinge on Structure A1 (Ry=1.5) in the x-axis direction of 79.352 mm is smaller than Structure B1 (Ry=1.78) by 94.01 mm. This indicates that the plastic hinge of Structure A1 is formed earlier than Structure B1.

Keywords: Earthquake resistant steel building structures; Pushover analysis; SNI 7860:2020; Steel over strength ratio; Structural behavior

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1. Introduction

Steel is a material that is widely used as a building construction material besides concrete. Compared to concrete, steel has the advantage of having a higher strength-to-weight ratio so that overall it will produce a lighter building structure [1]. In addition, steel also has ductile properties so steel material is very suitable to be used as an earthquake-resistant building structure.

The planning of earthquake-resistant steel building structures based on SNI 7860:2020 requires that the required strength of structural elements be determined based on the expected yield stress, Ry.Fy and the expected tensile stress, Rt.Fu. Based on the provisions of SNI 7860:2020, the value of hot rolled steel material with ASTM A36 grade or equivalent is 1.5 for yield strength, Ry, and 1.2 for tensile strength, Rt [2]. However, the Ry and Rt values contained in SNI 7860:2020 are not yet based on the testing of steel products in Indonesia and still follow the provisions of AISC 341-16. Where the values of Ry and Rt in AISC are the results of tensile strength testing of steel products in America [3]. The quality of steel in the form of Ry and Rt values in SNI should adjust to steel products in Indonesia because the quality of steel between Indonesia and America is not necessarily the same.

The yield strength value is used in structural planning with the concept of capacity design, which is to determine the structural elements that behave elastically and the structural elements that are designed to experience melting as a place for the formation of plastic hinge during a strong earthquake [4, 5]. This concept aims to ensure the formation of plastic hinge at both ends of the beam during a strong earthquake. Therefore, columns should be designed stronger than beams (Strong Column-Weak Beam) so that plastic hinge are only formed at both ends of the beam and the expected collapse mechanism of beam sway mechanism occurs. Conversely, if the beam is designed to be stronger than the column (Strong Beam-Weak Column), a plastic hinge will form at the column which can lead to a column sway mechanism collapse.

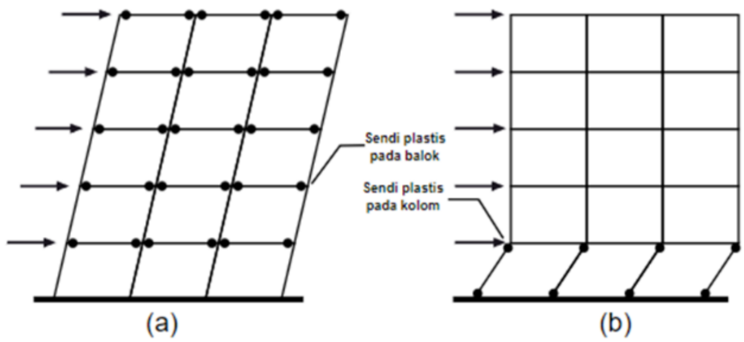

Figure 1. *Beam sway mechanism (a), column sway mechanism (b)*

A yield strength value greater than the standard rule will jeopardize the planning of structural elements, which can cause a plastic hinge formation mechanism that is not in accordance with the planning which can result in structural failure or can cause waste of construction costs if the yield strength value is lower than the standard rule [3]. Therefore, it is necessary to test steel materials in the planning of earthquake-resistant steel building structures to determine the value of the strength of the steel material to be used.

This study was conducted to determine the comparison between the value of steel overload based on the provisions of SNI 7860: 2020 and the results of tensile strength testing and to determine the difference in structural behavior between the use of steel overload based on the provisions of SNI 7860: 2020 and the results of tensile strength testing applied to the analysis of steel building structures with the SMF system (Special Moment Frame). The structural behavior in question is the SCWB (Strong Column-Weak Beam) ratio, the mechanism of plastic hinge formation, and the level of structural performance to determine the behavior of the structure under nonlinear conditions [6].

2. Materials and Experiment Methods

This research uses an experimental method, which is a method carried out by testing the effect of using the steel over-strength ratio from tensile test on structural behavior. This research begins by collecting data from SNI 7860: 2020 to obtain data on steel over strength ratio in the form of yield strength ratio (Ry) and tensile strength ratio (Rt). Then collect data on the results of steel tensile strength testing with ASTM A36 / BJ 41 steel quality in the form of yield stress (Fy) and tensile stress (Fu) [7]. After that, calculations are made to obtain the value of the yield strength ratio (Ry) and tensile strength ratio (Rt). The value of the steel over-strength ratio can be written in the following equation:

$$Ry = Fye/Fy \tag{1}$$

$$Rt = Fue/Fu \tag{2}$$

Where:

Ry : Ratio of actual yield stress to nominal yield stress

Rt : Ratio of actual tensile stress to nominal tensile stress

Fye : Actual yield stress (MPa)

Fue : Actual tensile stress (MPa)

Fy : Nominal yield stress (MPa)

Fu : Nominal tensile stress (MPa)

Furthermore, modeling the building structure in the form of a 3-story building with a steel structure that functions as an office building. The connection system in the building structure uses a pre-qualified connection based on SNI 7972: 2020 [8]. The building structure is divided into 4, namely structures A1, B1, A2, and B2 (Table 1) which are distinguished based on the steel profile of the main beam and the difference in the use of steel over-strength ratio by changing the steel grade in the Material Property section (Figure 2). The modeling of the structure into 4 parts is intended to determine the behavior comparison between the four structural models due to the difference in steel over strength ratio.

Table 1. Building structure modelling object

Structure	Steel Over Strength Ratio	Main Beam Profile
A1	SNI 7860:2020	IWF 300x150x6,5x9
B1	Tensile Test Results	IWF 300x150x6,5x9
A2	SNI 7860:2020	IWF 200x100x5,5x8
B2	Tensile Tst Results	IWF 200x100x5,5x8

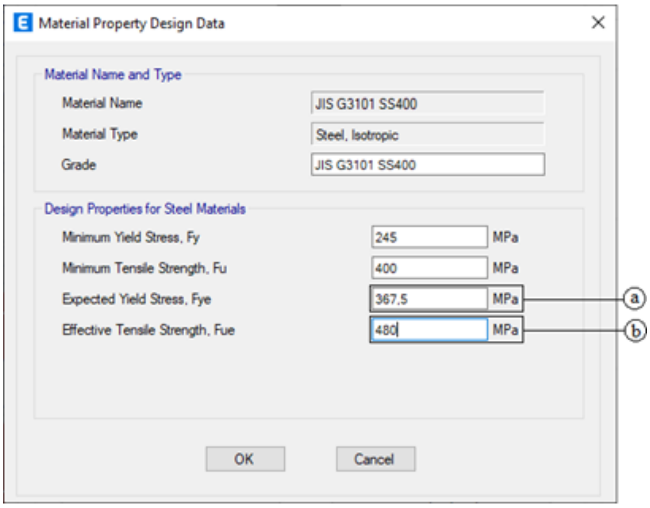

Figure 2. *Material Property* in ETABS

Description:

a : Actual yield stress, Fye

b : Actual tensile stress, Fue

3. Results and Discussion

3.1. Tensile Test Results

Based on the tensile test results, IWF 300x150x6.5x9 with BJ41 grade obtained a yield stress value of 435.29 MPa and a maximum tensile stress of 541.62 MPa. The IWF 200x100x5.5x8 steel profile with BJ41 grade obtained a yield stress value of 386.23 MPa and a maximum tensile stress of 513.08 MPa. The following is a recapitulation of steel quality data from tensile strength testing results and comparison with the provisions of SNI 7860: 2020.

Table 2. Recapitulation of steel grade tensile test results

Profile	F_{ye} (MPa)	F_{ue} (MPa)	Ry (F_{ye}/F_y)	Rt (F_{ue}/F_u)
IWF 300x150	435,29	541,62	1,78	1,35
IWF 200x100	386,23	513,08	1,58	1,28

Table 3. Comparison over-strength ratio of steel based on SNI 7860:2020 with over-strength ratio of steel from tensile test results

Profile	SNI 7860:2020		Tensile Test		Difference (%)	
	Ry	Rt	Ry	Rt	Ry	Rt
IWF 300x150	1,5	1,2	1,78	1,35	18,45	12,84
IWF 200x100	1,5	1,2	1,58	1,28	5,10	6,89

3.2. Structure Modelling

The structure of the building to be analyzed is modeled in 3-dimensional form with the ETABS program. Elements of the structure are modeled in the form of columns, beams, floor slabs, and stairs. The following are structural modeling data and building structure modeling results.

- Building Function : Office
- Location : Palembang
- Number of Floors : 3 Floors
- Dimensions (P x L) : 12 m x 8 m
- Building Height : 9 m
- Height per Floor : 3 m
- Steel Grade : BJ 41

Table 4. Data of steel material quality in structural modelling

Structure	Elements	Profile	Expected Stress	
			Fye (MPa)	Fue (MPa)
A1	Column	H 400x400	367,5	480
	Beam	IWF 300x150	**367,5**	**480**
B1	Column	H 400x400	367,5	480
	Beam	IWF 300x150	**435,29**	**541,62**
A2	Column	H 400x400	367,5	480
	Beam	IWF 200x100	**367,5**	**480**
B2	Column	H 400x400	367,5	480
	Beam	IWF 200x100	**386,23**	**513,08**

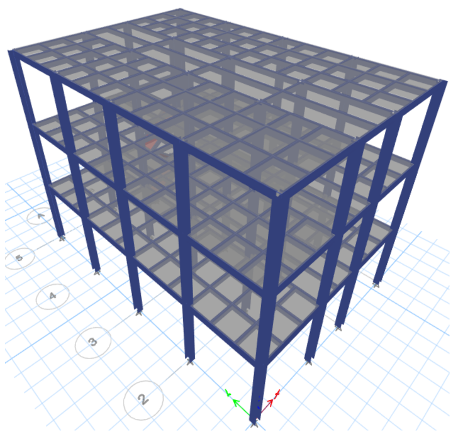

Figure 3. 3D modelling results

3.3. Linear Statics Analysis Results

The following are the results of the linear static analysis in the form of the largest SCWB value located at column 14 of the 1st floor.

Table 5. SCWB value of the structure

Structure	A1	B1	A2	B2
B/C Ratio	0,806	0,955	0,312	0,328
Location	Story1, C14		Story1, C14	
Difference	18,49%		5,13%	

Based on the table of SCWB ratio values above, the SCWB value of structures that use more strength based on SNI 7860: 2020, namely A1 and A2, is smaller than the SCWB value of structures that use more strength based on the tensile test results, namely B1 and B2. There was an increase in the SCWB value between structures A1 and B1 by 18.49%. While between A2 and B2 structures there is an increase in SCWB value by 5.13%.

Structures A1 and A2 that use the steel over-strength ratio based on SNI 7860:2020 more easily achieve the Strong Column-Weak Beam collapse mechanism compared to structures B1 and B2 that use the steel over-strength ratio based on the tensile test results.

3.4. Pushover Analysis Results

The following are the results of the pushover analysis in the form of plastic hinge distribution of structure A1 (Table 6) and structure B1 (Table 7).

Table 6. Pushover X plastic hinge distribution of A1 structure

Step	Monitored Dis. (mm)	Base Force	A-B	B-C	C-D	D-E	>E	A-IO	IO-LS	LS-CP	>CP	Total
0	0	0	306	0	0	0	0	306	0	0	0	306
1	79,352	2202,9	303	3	0	0	0	306	0	0	0	306
2	158,924	3368,3	261	45	0	0	0	266	40	0	0	306
3	243,683	3996,0	242	62	2	0	0	246	50	10	0	306
4	243,693	3750,4	242	62	0	0	2	246	50	8	2	306
5	249,449	3835,2	242	61	1	0	2	244	52	8	2	306
6	249,459	3731,7	242	61	0	0	3	244	52	7	3	306

7	261,897	3844,6	238	63	2	0	3	241	55	7	3	306
8	261,907	3728,6	238	63	0	0	5	239	57	5	5	306
9	271,764	3797,3	235	65	1	0	5	238	58	5	5	306
10	271,257	3741,0	235	64	1	0	6	237	59	4	6	306

Table 7. Pushover X plastic hinge distribution of B1 structure

Step	**Monitored Dis. (mm)**	**Base Force**	**A-B**	**B-C**	**C-D**	**D-E**	**>E**	**A-IO**	**IO-LS**	**LS-CP**	**>CP**	**Total**
0	0	0	306	0	0	0	0	306	0	0	0	306
1	94,01	2609,8	303	3	0	0	0	306	0	0	0	306
2	190,228	4010,2	260	46	0	0	0	276	30	0	0	306
3	237,012	4363,9	246	58	2	0	0	266	30	10	0	306
4	237,022	4085,3	246	58	0	0	2	266	30	8	2	306
5	243,268	4181,1	246	56	2	0	2	266	30	8	2	306
6	243,278	3982,5	246	56	0	0	4	266	30	6	4	306
7	254,767	4107,3	246	54	2	0	4	266	30	6	4	306
8	254,777	3976,9	246	54	0	0	6	266	29	5	6	306
9	268,805	4089,2	246	52	2	0	6	264	27	9	6	306
10	268,815	3995,7	246	52	0	0	8	264	26	8	8	306
11	283,727	4040,3	246	50	0	0	10	248	28	20	10	306
12	310,188	4195,1	233	60	3	0	10	246	30	20	10	306

Based on Table 6, the initial formation of plastic hinge of structure A1 in the x direction occurs at step 1/10 where the structure experiences a deviation of 79.352 mm and there are 3 plastic hinge formed. The initial formation of plastic hinge of structure B1 (Table 7) in the x direction occurs at step 1/12 where the structure experiences a deviation of 94.01 mm and there are 3 plastic hinge formed. The following is a recapitulation of the initial formation of plastic hinge on structures A1, B1, A2 and B2.

Table 8. Recapitulation of the initial formation of plastic hinge of structures A1 and B1

Axis Direction	**X**		**Y**	
Structure	**A1**	**B1**	**A1**	**B1**
Deviation (mm)	79,352	94,01	12,265	19,313
***Base Force* (kN)**	2202,9	2609,8	2183,4	2592,5
Number of Plastic Hinge	3	3	1	1
Step-	1/10	1/12	1/11	1/12

Based on the table above, the deviation value at the time of initial melting in structure A1 of 79.352 mm is smaller than that of structure B1 which is 94.01 mm. This shows that the formation of plastic hinge in structure A1 occurs earlier than structure B1.

Table 9. Recapitulation of the initial formation of plastic hinge of structures A2 and B2

Axis Direction	**X**		**Y**	
Structure	**A2**	**B2**	**A2**	**B2**
Deviation (mm)	104,174	109,496	20,13	21,189
***Base Force* (kN)**	1019,1	1071,2	734,2	772,8
Number of Plastic Hinge	2	2	1	1
Step-	2/24	2/24	1/14	1/12

The same thing happened to structures A2 and B2 where the deviation at the time of initial formation of plastic hinge in A2 structure of 104.174 mm was smaller than that of the B2 structure which amounted to 109.496 mm. This indicates that the formation of plastic hinge in the A2 structure occurs earlier than the B2 structure. The earlier formation of plastic hinge in structures A1 and A2 indicates that the Strong Column-Weak Beam collapse mechanism in structures that use stronger steel according to SNI 7860: 2020 (A1 and A2) is easier to achieve than structures that use stronger steel tensile test results (B1 and B2).

3.5. Structure Performance Level

Determination of structural performance levels using the ATC-40 method, which is based on performance points on the ADRS (Acceleration Displacement Response Spectra) graph [9]. The ADRS graph contains the intersection point between the demand response spectrum curve and the pushover capacity curve called the performance point. The following are the structural performance levels A1, B1, A2 and B2.

Table 10. Structure performance levels A1 and B1

Axis Dir.	**Parameters**	**Structure**			
		A1	**B1**	**A2**	**B2**
X	Performance Point, Δm (mm)	15,6	15,6	39,6	39,6
	Total Drift	0,0017	0,0017	0,0044	0,0044
	Performance Level (ATC-40)	IO	IO	IO	IO
Y	Performance Point, Δm (mm)	12,1	12,1	24,9	24,9
	Total Drift	0,0013	0,0013	0,0028	0,0028
	Performance Level (ATC-40)	IO	IO	IO	IO

Based on the table above, it can be seen that there is no difference in the value of performance points and performance levels between structures that use the steel over strength ratio provisions of SNI 7860: 2020 and structures that use the steel over strength ratio from the tensile test, that are structure A1 vs B1 and structure A2 vs B2.

4. Conclusions

Based on the results of the analysis that has been carried out regarding the results of tensile strength testing and structural analysis, the following conclusions can be drawn:

- Based on the tensile test results, the IWF 300x150x6.5x9 steel profile has a yield strength ratio (Ry) of 1.78 greater than the SNI provisions of 1.5 with a difference of 18.45% and a tensile strength ratio (Rt) of 1.35 greater than the SNI provisions of 1.2 with a difference of 12.84%
- The SCWB value of column 14 floor 1 in structure A1 (Ry = 1.5) is 0.806, smaller than that of structure B1 (Ry = 1.78) of 0.955 so that the Strong Column-Weak Beam collapse mechanism in structure A1 can be more easily achieved than structure B1
- The deviation value at the time of initial melting of the x-axis direction A1 structure of 79.352 mm is smaller than the x-axis direction B1 structure of 94.01 mm. This shows that the process of forming plastic hinge in structure A1 is earlier than structure B1 so that the Strong Column-Weak Beam collapse mechanism in structure A1 is easier to achieve than structure B1
- The total drift value of structure A1 is 0.0017 in the x direction and 0.0013 in the y direction so the performance level of structure A1 is Immediate Occupancy. While the total drift value of structure B1 is 0.0017 in the x direction and 0.0013 in the y direction so that the performance level of structure B1 is Immediate Occupancy

Conflicts of Interest: The authors declare no conflict of interest.

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