



NON-LINEAR ANALYSIS OF FAILURE MECHANISM OF STEEL TRUSS BRIDGE

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ABSTRACT

Failure of steel truss bridge members could lead to a further damage or even to the collapses of the bridge. The collapse of a bridge often occurred in Indonesia due to various factors, such as over loads, dynamic live loads, earthquake and deteriorated material. Push-over analysis was used to analyze the failure mechanism of a steel truss bridge, which gave a point load at the mid-span and to be gradually increased. Six models of the bridge were analyzed, which are three continuous span and three single span bridge models. The study shows that the failures of the continuous steel truss bridge occurred in the diagonal chord of the end portal. All single span bridge models failure occurred on the chord at the mid span. The performance level of structure shows all models of the truss bridges are in the Immediate Occupancy (IO) based on the target displacement of FEMA 356. The actual ductility occurred in all models of bridges is compliant with Indonesian Standard.

Keywords: pushover analysis, steel truss bridge, failure mechanism, ductility.

INTRODUCTION

Steel truss bridge had been built in Indonesia before the year of 1945. Many of them have exceeded the design age limit and need to be replaced or repaired. The growth of transportation, over-load cases and lack of maintenance caused many steel truss bridges to be damaged [1]. The latest case of steel truss bridge collapse has occurred at Probolinggo, Indonesia on March 3rd, 2015. The cause of collapse could not withstand with the load when a truck of a fully sand that passed over it [2]. Not only in Indonesia, the case of bridge collapse also occurred in the USA. The I-35W bridge over the Mississippi river, Minneapolis USA was collapsed on August 1th, 2007. The cause of sudden collapse is due to a connection at one of the gusset plates failure. Corrosion

of the gusset plate and increase load of the bridge were the possible cause of the collapse on the bridge [3, 4].

Failure of steel truss bridge members could lead to further damage or even to the collapses of the bridge. For the reason, this paper presented the non-linear analysis of a failure mechanism of a single span and continuous span steel truss bridges using the pushover analysis.

TRUSS BRIDGE MODEL

Figure-1 and 2 show the truss bridge model. The model is classified in two Warren's type conditions. First, A-model is designed as continuous span bridge with a total length of 120 m that is divided into 3 types of group,

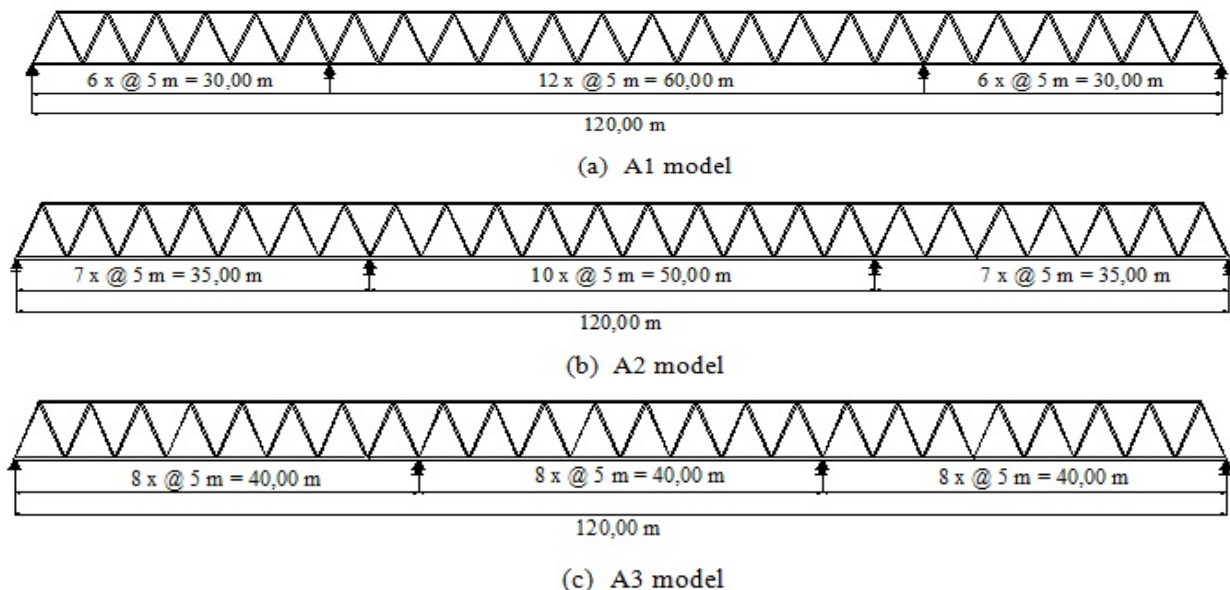


Figure-1. Side view of bridge A-model.



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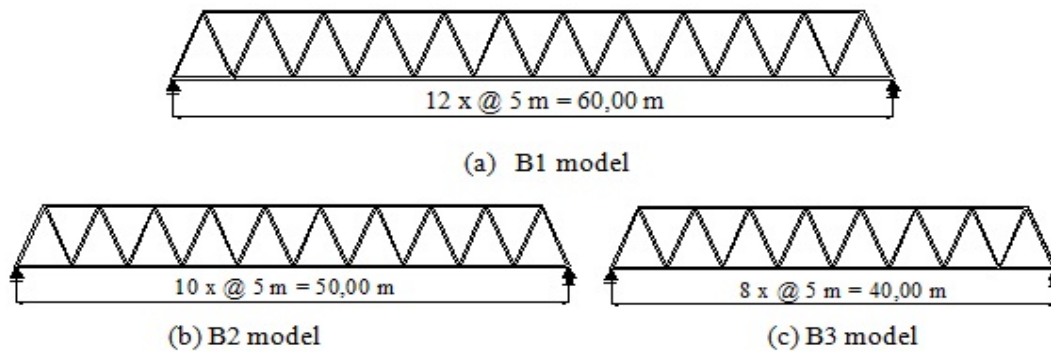


Figure-2. Side view of bridge B-model.

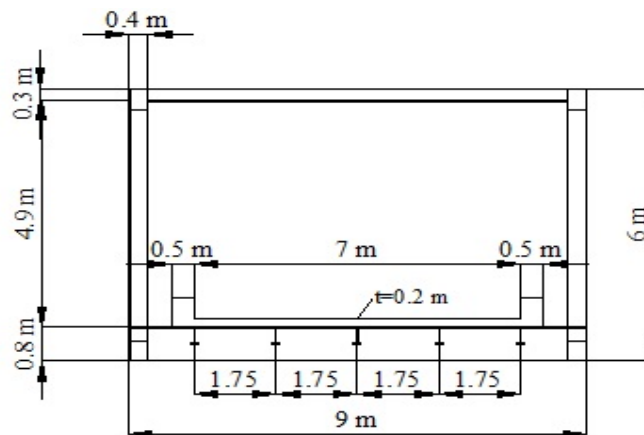


Figure-3. Cross section of bridge model.

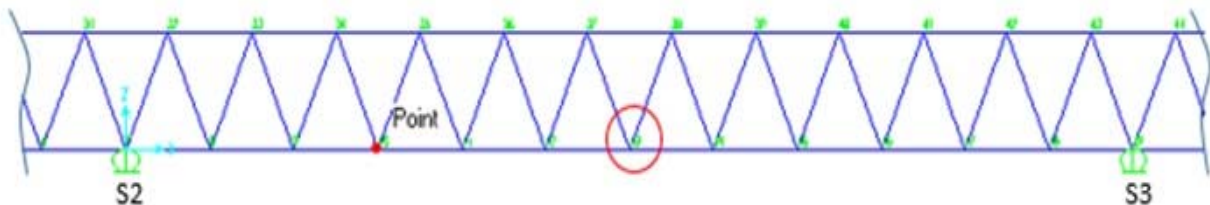


Figure-4. A reference point of A1-model.

namely A1, A2 and A3. Second, B-model is design as a single span bridge with varied of length 60 m, 50 m and 40 m chronologically called as B1, B2 and B3.

Bridge A1-model has a span ratio of 1:2:1 with a center span 60 m and a side span of 30 m. Then, bridge A2-model with 1:1.43:1 span ratio is arranged the center span of 50 m with the side span of 35 m. For bridge A3-model, it has span ratio 1:1:1. Typically, both of the center span and the side span are designed by 40 m.

The following bridge design is bridge B-model. The bridge B1-model is composed by 12 members of 5 m trusses. Subsequently, for B2-model and B3-model, the length of the bridges are illustrated decreased. Each member is installed by 10 trusses and 8 trusses with the equal element trusses 5 m per element.

Another parameter is also specified to conduct a bridge performance level as progressive collapse analysis to clarify the effect of each bridge model. The fixed

dimension for all of models are the height and the wide of the bridge, sequentially 6 m and 9 m. Figure-3 is presented the exemplary of bridge cross section model. It is also illustrated the structural members and deck system. Reinforce concrete slab is assumed for the bridge deck using 200 mm thickness. The steel grades in Indonesian industrial standard is used [6] with young's modulus of 2.1×10^5 MPa, yield stress of 290 MPa and ultimate steel stress of 500 MPa. The dimension of the members of the truss bridge is calculated based on the Indonesian standard [5, 6, 7].

NONLINIER ANALYSIS (PUSHOVER ANALYSIS)

Nonlinear analysis is used to adjust the post-yielding behavior of a structure, where the applied loads are gradually increased by a factor until one lateral displacement target of the reference point is reached [8, 9]. The result of the nonlinear static pushover analysis is a



curve that describes the relationship between the base shear forces and the displacement at reference point, which is at the mid-span of the bridge. It can be seen in Figure-4.

The hinge properties of the truss beam are defined as axial only (defined as *Auto P*), except at the end portals. The hinge properties of the end portal are defined as bending elements (defined as *Auto PM2*).

The load of the bridge for the pushover analysis is the dead loads from the self-weight of the bridge components. The loads are modelled as a point on the truss bridge. The loading is as follows:

- Joint load from the cross girders, slab, stringers and bottom bracing. The value of the point load is 451.80 kN.

- Joint load from the top bracing. The value of the joint load on the top connection is: 5.39 kN.

The loading of the model is expressed in Figure-5. The analytical model is a two-dimensional model and only the main truss of the structure (Figures-1 and 2) is considered.

NONLINIER ANALYSIS RESULT

Target of displacement

Target of displacement of the bridge structure should be determined earlier before starting the nonlinear static analysis. Equation (1) is used to calculate the target of displacement [9].

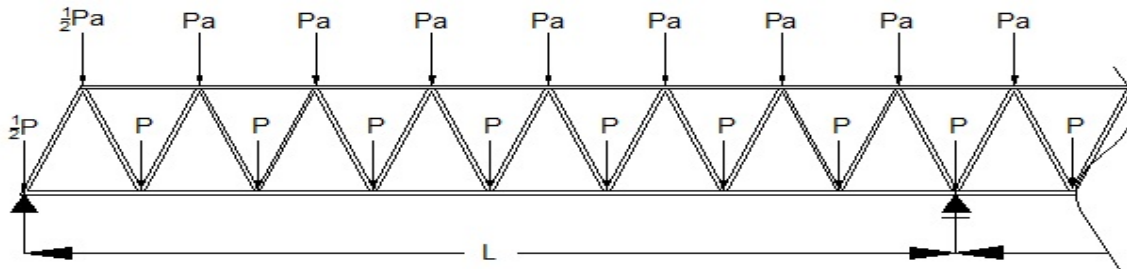


Figure-5. Structure loading scheme.

Table-1. Target of displacement for each model.

Model	C ₀	C ₁	C ₂	C ₃	S _a	T _e (detik)	d _T (cm)
A1	1.0	1.0	1.0	1.0	1.104	0.1791	10.31
A2	1.0	1.0	1.0	1.0	1.104	0.1284	7.34
A3	1.0	1.0	1.0	1.0	1.104	0.0818	2.72
B1	1.0	1.0	1.0	1.0	1.104	0.2527	20.19
B2	1.0	1.0	1.0	1.0	1.104	0.1828	11.03
B3	1.0	1.0	1.0	1.0	1.104	0.1258	6.96

Table-2. Damage level of the structure.

Description	Symbol	Illustration
B	●	Structures can operate normally. This Performance Level (PL) are expected to sustain minimal or no damage to their structural and non-structural components.
IO	●	This performance level is expected to sustain minimal or no damage to the structural elements and only minor damage to the non-structural components. While it would be safe to reoccupy a structure meeting this target PL immediately following a major load.
LS	●	Structures meeting this level may experience extensive damage to structural and non-structural components. Repairs may be required before preoccupancy of the structure, and may be deemed economically impractical.
CP	●	Little residual stiffness and strength and large permanent drifts occurred. Some exits were blocked and the structure nearly collapses.
C	●	The maximum limit in the structure withstand the major loads.
D	●	The structure is not able to withstand the lateral loads but it was still able to withstand the force of gravity.
E	●	The structure is damage



$$\delta_T = C_0 C_1 C_2 C_3 S_a \left(\frac{T_e}{4\pi} \right)^2 g \quad (1)$$

where:

- C_0 = modification factor relates the spectral displacement and the roof displacement. Base on [9], the value of C_0 is 1.0.
- C_1 = Modification factor to relate expected maximum inelastic displacements to displacements calculated for a linear elastic response, where the value of C_1 is 1.0 if $T_e \geq T_s$.
- C_2 = Modification factor to represent the effect of pinched hysteretic shape, stiffness degradation and strength deterioration on the maximum displacement response, where C_2 is 1.0.
- C_3 = Modification factor to represent increased displacements due to dynamic P-Δ effects. For the structure with positive post-yield stiffness, shall be set equal to 1.0.
- S_a = Response spectrum acceleration, at the

effective fundamental period and damping ratio of the building in the direction under consideration.

T_e = The effective fundamental period

Based on [7], the value of S_a obtained from the equation below:

$$S_a = C_D \times S_0 = 0.92 \times 1.2 = 1.104. \quad (2)$$

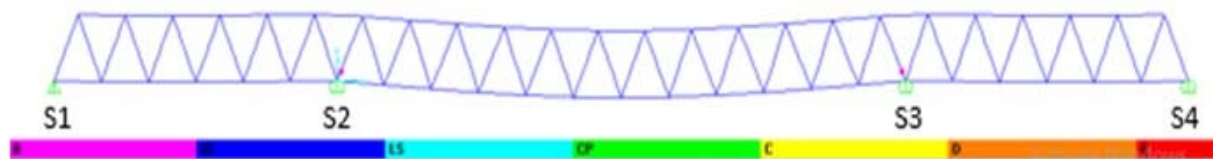
The target displacement of the bridge models can be seen in Table 1.

Performance level of structure

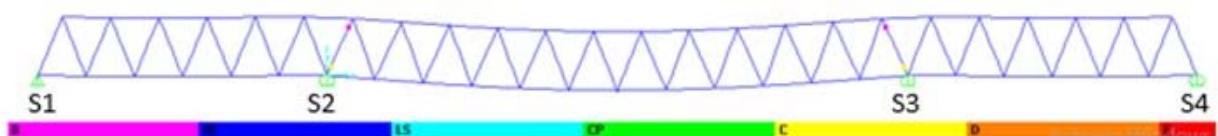
The level of damage to structural elements can be observed from the results of the analysis. Determination of the performance level of the bridge is based on the safety level for road users in the bridge during and after a load toward the damage of the structure. The performance level of a structure is set as follows in each model [5, 6]:

Table-3. Structural performance of A1-model.

Step	Displacement (cm)	Base Force (T)	A - B	B - IO	IO-LS	LS - CP	CP - C	C - D	D - E	>E	Total
0	9.839	0.00	101	0	0	0	0	0	0	0	101
1	14.795	601.30	99	2	0	0	0	0	0	0	101
2	15.258	653.87	97	4	0	0	0	0	0	0	101
3	15.347	653.92	97	2	0	0	0	2	0	0	101
4	16.570	3218.40	95	6	0	0	0	0	0	0	101
5	15.357	655.14	95	6	0	0	0	0	0	0	101
9	15.508	669.41	95	4	0	0	0	2	0	0	101
10	15.875	669.01	95	4	0	0	0	2	0	0	101
11	19.253	667.19	95	2	2	0	0	0	2	0	101
12	19.253	667.19	95	2	2	0	0	0	0	2	101



(a) First yield at the first step



(b) Reach the performance level at the third step

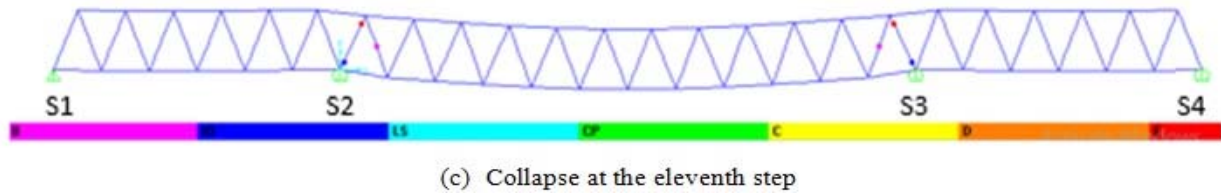


Figure-6. Plastic hinge characteristic with performance level information - A1 model.

Table-4. Structural performance of A2-model.

Step	Displacement (cm)	Base Force (T)	A - B	B - IO	IO-LS	LS - CP	CP - C	C - D	D - E	>E	Total
0	9.839	0,00	101	0	0	0	0	0	0	0	101
1	14.795	601.30	99	2	0	0	0	0	0	0	101
2	15.258	653.87	97	4	0	0	0	0	0	0	101
3	15.347	653.92	97	2	0	0	0	2	0	0	101
4	16.570	3218.4	95	6	0	0	0	0	0	0	101
5	15.357	655.14	95	6	0	0	0	0	0	0	101
6	15.599	684.58	95	4	0	0	0	2	0	0	101
8	16.570	3218.4	95	6	0	0	0	0	0	0	101
9	15.508	669.41	95	4	0	0	0	2	0	0	101
10	15.875	669.01	95	4	0	0	0	2	0	0	101
11	19.253	667.19	95	2	2	0	0	0	2	0	101
12	19.253	667.19	95	2	2	0	0	0	0	2	101

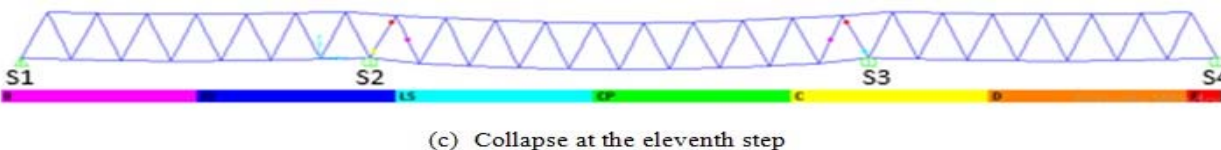
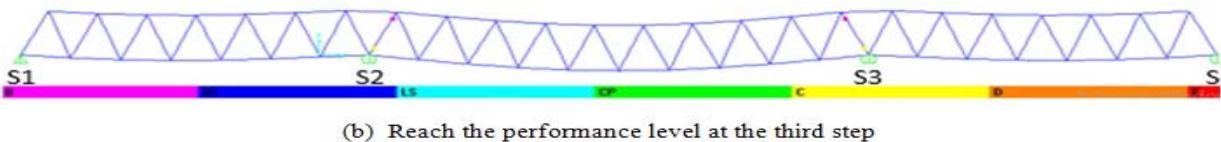
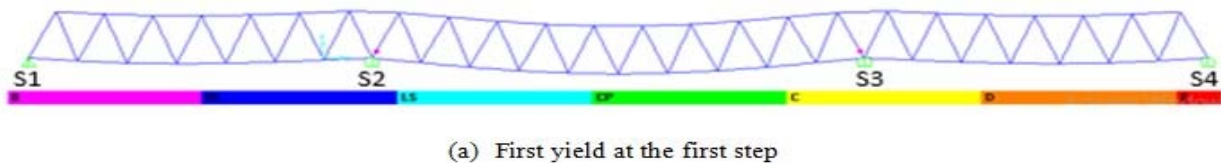


Figure-7. Plastic hinge characteristic with performance level information - A2 model.

a) A1-model

Target displacement of the A1-model according to [9] is 10.31 cm as illustrated in Table-3. The performance level of the structure is at the boundary of Immediate occupancy (IO). Based on [9], the IO means no damage to structural components and can be used immediately.

The target displacement exceeded at step 1 as presented in Figure-6a. The first yielding occurred at the bottom of the diagonal chord at the end frame. In step 3 as drawn in Figure-6b, it reached a performance level which is occurred at the upper of the diagonal chord at the end

frame. In step 12 as shown in Figure-6c, the top of diagonal chord at the end frame was collapse, and the tensile diagonal chord near S2 and S3 supports are applied a plastic hinge.

b) A2-model

In this model, bridge A2-model has nearly the same dimension as the A1-model which expressed the center span of 50 m. Target displacement of the A2-model based on FEMA 356 [9] is 7,34 cm. Afterwards, it is compared to the first step data which has been passed through the value of target displacement. The performance



level of the structure is still at the boundary of B - IO. The structural components are implied no damage and could be used immediately as well.

Figure-7a drawn the first yield condition. it is occurred at the bottom of diagonal chord imminent to S2 and S3 supports. From that condition, the A2-model is given a similar result as A1-model. Another analysis which are presented on Figures-7b and 7c also giving the similar result. In that case, the differences of span ratio of A2-model should be evaluated smaller than 50 m. The further condition, the bridge A3-model is presented the same variety of span length which is allocated 40 m for both center span and side span.

c) A3-model

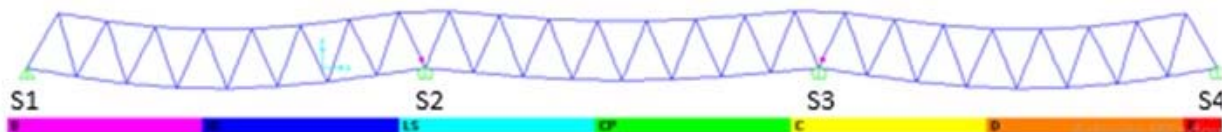
As served in Table-5, the structural performance of A3-model is cited [9] 2,72 cm. That value become a

compulsory parameter that should be managed. Collapse processes is evaluated by both data as well.

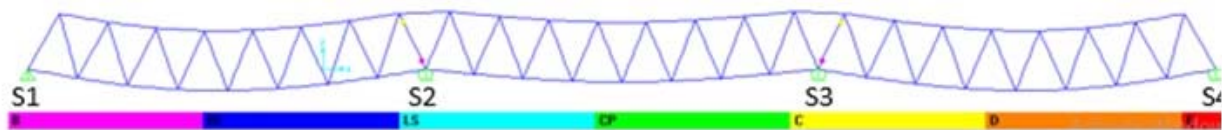
Furthermore, Figures-8a, 8b and 8c respectively expressed that the bottom chord at support S2 and S3 become yield in tension at first. Then, the upper chord become yield in tension in the following as well. In that matter, the structural performance level of its structure has been reached. Next, compression yield appeared near the intermediate frame in area of the span center. Finally, after reaching the performance level, the structure is collapse. The diagonal member fully damaged near the S2 and S3. The maximum tension happened when the increment loading increases. One of the span sharply fell underneath and one another is upraised because of the damage at support S2 and S3.

Table-5. Structural performance of A3-model.

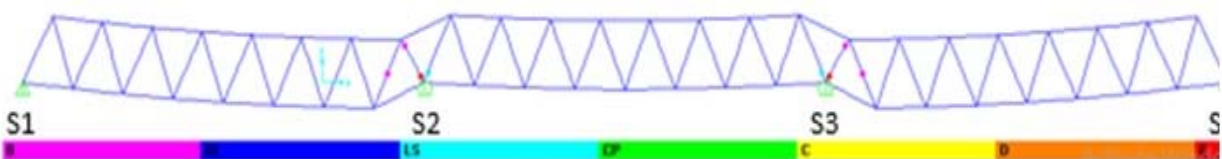
Step	Displacement (cm)	Base Force (T)	A - B	B - IO	IO-LS	LS -CP	CP - C	C - D	D - E	>E	Total
0	2.6656	0.00	102	0	0	0	0	0	0	0	102
1	3.1622	217.91	100	2	0	0	0	0	0	0	102
2	3.2298	245.81	98	4	0	0	0	0	0	0	102
3	3.2443	246.56	98	2	0	0	0	2	0	0	102
4	3.6064	2760.1	96	6	0	0	0	0	0	0	102
5	3.2453	247.00	96	6	0	0	0	0	0	0	102
6	3.2603	247.70	96	6	0	0	0	0	0	0	102
7	3.3447	284.2	96	4	0	0	0	2	0	0	102
8	8.4773	488.70	94	4	0	2	0	0	0	2	102



(a) First yield at the first step



(b) Reach the performance level at the third step



(c) Collapse at the eighth step

Figure-8. Plastic hinge characteristic with performance level information - A3 model.

**d) B1-model**

B-model or a single span model is given a shorter step evaluation than A-model. It is also given a simple prediction of collapse condition which will be happened at the center of the span. Table-6 is expressed the structural performance based on the step parameter. The allowable displacement is still referred to FEMA 356 of 20,19 cm. In fact, both data of analyses are considered and it is shown that performance level of the structure is fulfilled at the boundary B-IO. There is no damage to the structural component which is well-considered to be used shortly.

B1-model case with 60 m length is presented in Figures-9a, 9b and 9c in sequence. First condition, the upper chords at the span center become yield in tension. It is illustrated by the implied purple color on the truss, i.e. A-B. Then, second condition, when the load amplification is reached the performance level, the color point is changed to be in ultimate strength condition, specifically B-IO to C-D. Finally, the third condition, the maximum tensile strain is occurred by the loading mechanism. The failure is located in the same center of span that leads significant damage on the structure (collapse).

e) B2-model

In B2-model, the total length of the span is allocated 50 m. The target displacement is also considered according to FEMA 356 [9] that is listed of 11,03 cm. While the displacement of pushover analysis results is

referred to Table-7 which is being compared to understand the performance level of its structure. The comparison is implied that the performance structure is at the boundary B-IO. As the matter of fact, there is no concerned damage of the structural components. The structural system could still be used immediately.

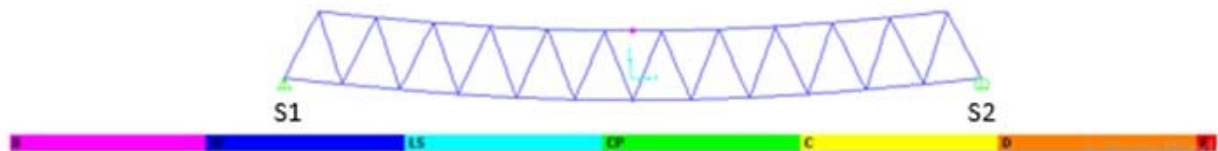
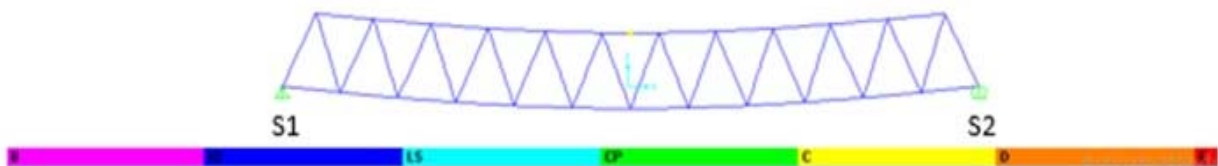
The failure mechanism is expressed by Figures 10a, 10b and 10c using 50 m length of the structure. The failure is almost given a typical condition with the B1-model. The upper chords at the span center became yield in tension at first. Finally, when the load amplification reached, the upper chord buckled at the span center is in the performance level in B-IO to C-D condition. Then, the maximum tensile strain at the upper chord is collapse in the further. The failure is located in the same center of span that leads a further damage or collapse on the structure.

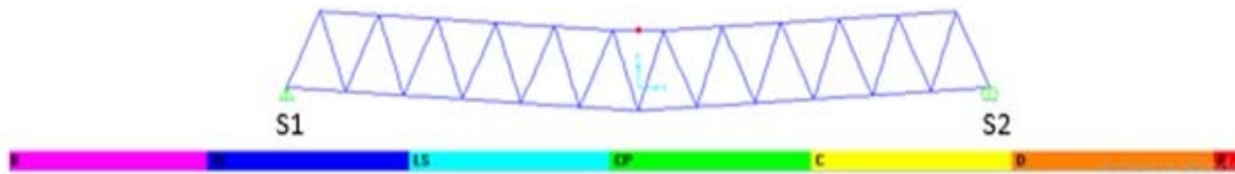
f) B3-model

In B3-model, the total length of the span is changed to 40 m length. It is also implied the difference of target displacement of 6,96 cm [9]. The pushover analysis result (seen Table-8) is compared to classify the performance level of its structure. The result shown that the performance level occurred at the boundary B-IO as well.

Table-6. Structural performance of B1-model.

Step	Displacement (cm)	Base Force (T)	A - B	B - IO	IO-LS	LS -CP	CP - C	C - D	D - E	>E	Total
0	19.550	0.00	49	0	0	0	0	0	0	0	49
1	23.910	133.11	48	1	0	0	0	0	0	0	49
2	25.250	144.07	48	0	0	0	0	1	0	0	49
3	25.260	598.06	48	0	0	0	0	0	0	1	49

**(a) First yield at the first step****(b) Reach the performance level at the second step**

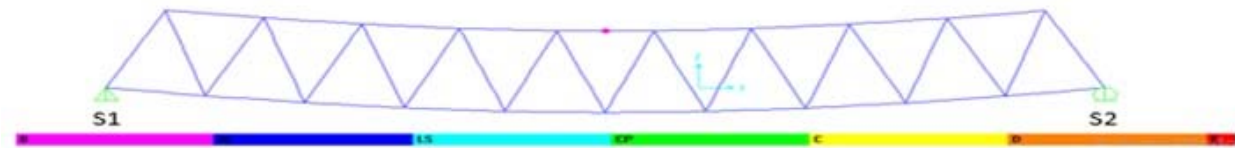


(c) Collapse at the third step

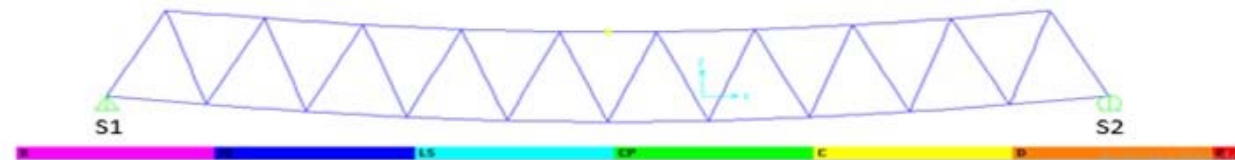
Figure-9. Plastic hinge characteristic with performance level information – B1 model.

Table-7. Structural performance of B2-model.

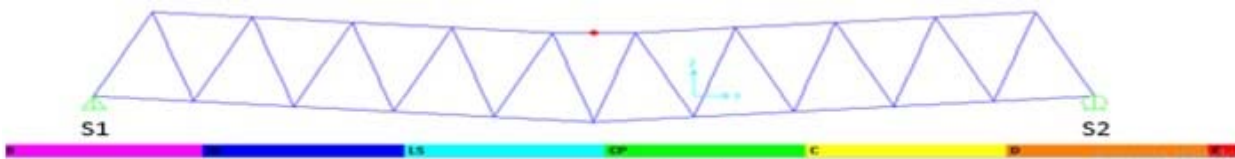
Step	Displacement (cm)	Base Force (T)	A - B	B - IO	IO-LS	LS -CP	CP - C	C - D	D - E	>E	Total
0	10.244	0.00	41	0	0	0	0	0	0	0	41
1	18.063	374.70	40	1	0	0	0	0	0	0	41
2	19.150	387.71	40	0	0	0	0	1	0	0	41
3	22.530	492.42	40	0	0	0	0	0	0	1	41



(a) First yield at the first step



(b) Reach the performance level at the second step



(c) Collapse at the third step

Figure-10. Plastic hinge characteristic with performance level information - B2 model.

Table-8. Structural performance of B3-model.

Step	Displacement (cm)	Base Force (T)	A - B	B - IO	IO-LS	LS -CP	CP - C	C - D	D - E	>E	Total
0	6.81	0.00	33	0	0	0	0	0	0	0	33
1	12.39	315.22	32	1	0	0	0	0	0	0	33
2	13.23	325.75	32	0	0	0	0	1	0	0	33
3	20.11	386.42	32	0	0	0	0	0	0	1	33

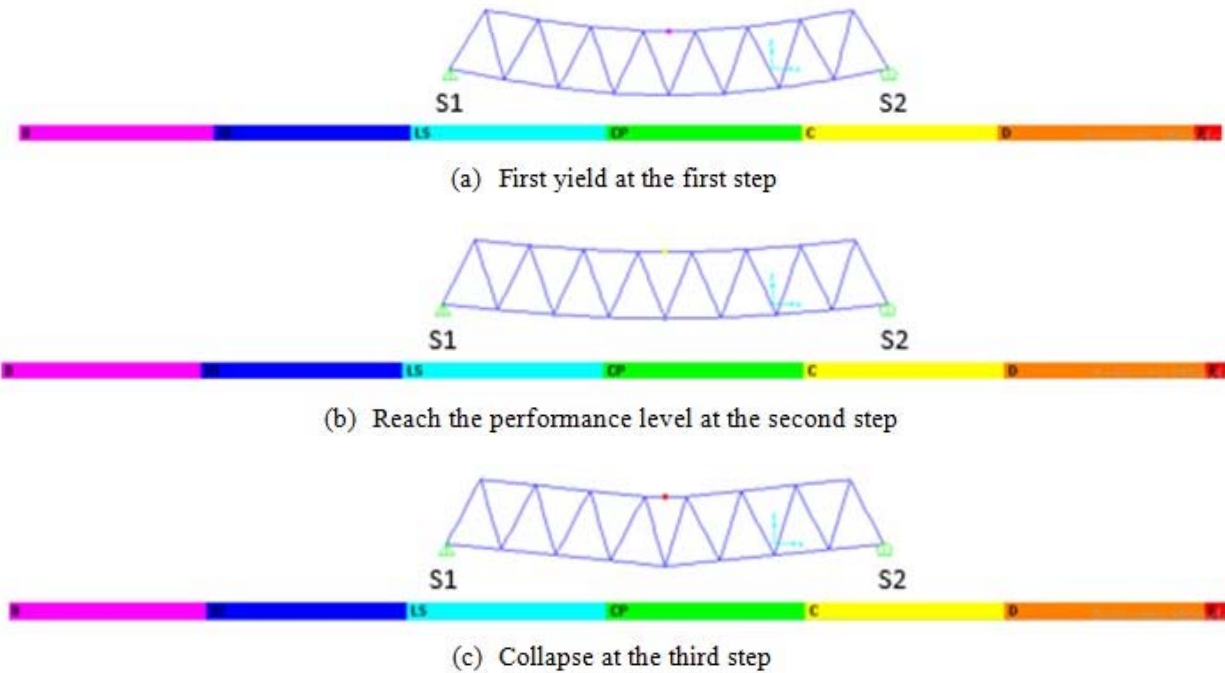


Figure-11. Plastic hinge characteristic with performance level information - B3 model.

Table-9. Ductility of bridge model for all designs.

Model	Base Force (T)		First yield	Ultimate point	ductility
	First yield	Ultimate Point	δ_y (mm)	δ_u (mm)	μ
A1	601.30	653.92	14.80	15.35	1.04
A2	980.03	1047.31	9.92	10.35	1.05
A3	217.91	246.56	3.16	3.24	1.07
B1	133.11	144.07	23.91	25.25	1.06
B2	374.70	387.71	18.06	19.15	1.07
B3	315.22	325.75	12.39	13.23	1.09

Figures-11a, 11b and 11c are illustrated the failure mechanism and the plastic hinge characteristic due to performance level. The value of B3-model is declined as the smallest according to displacement and base shear force. The upper chords at the span center became yield in tension at first with 12.39 cm displacement. Finally, when the load amplification reached at 325.75 t, the upper chord buckled at the span center is in the performance level in B-IO to C-D condition. Then, the maximum tensile strain at the upper chord is collapse in the further with 20.11 cm displacement. The failure is located in the same center of span that leads a further damage or collapse on the structure.

Ductility evaluation

The ductility of each bridge models can be calculated from the curve capacity. Equation (3) is used to calculate the ductility of the bridge.

$$\mu = \frac{\delta_u}{\delta_y} \quad (3)$$

μ = ductility

δ_u = the displacement at the ultimate point

δ_y = the displacement at the first yield point



In previous sections, damaged or collapse analysis was conducted for the two bridge models with different span ratios. It shows that collapse process and deformation depend on the span ratio.

In this section, ductility of the two bridge models is evaluated as shown in Table-9. The ductility factor μ of bridge is increased respectively from A1 to A3 and from B1 to B3. In A-model, A1 is given the smallest value due to base shear force and ultimate point event all A-models have the typical length. The opposite condition is presented by B-models, B1-model is plotted to have the smallest value of both base shear force and ultimate point. The comparisons of the ductility of the models were no significant differences, the reason is each model using the optimum section members for the truss bridges. The actual ductility of the models already met the requirements of standard [6].

CONCLUSIONS

The conclusion of this study is taken based on the nonlinear analysis using SAP 2000. The following conclusions were obtained as follow:

- The first failure of the continuous steel truss bridge is in the diagonal chord of the end of frame. While the first failure of the single steel truss bridge models is the upper chord at mid-span.
- The level of performance of all models are in the IO which means there are no damage to the structural components and the structures can be used immediately after excessive or sudden loads.
- The actual ductility to all models of the bridges already met the requirements of standard [6], where the ductility is about 1.07. These results could not show the comparison of the ductility of the models because of each bridge model using the optimum section members, even the bridge models have difference span length.

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