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LATERAL LOAD CAPACITY OF STEEL TRUSS COUPLING BEAM

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ABSTRACT: The utilizing of steel truss coupling beam is one of an alternative for coupling beam in coupled shearwall. This paper presents an experimental study of steel truss coupling beam with span to depth ratios of 1.78 that tested under lateral cyclic loading at the laboratory. The objective of this research is to study the behaviour of steel truss coupling beam in coupled shearwall. The specimen are designed considering several factors such as span to depth ratio, strength of material, the dimension of double steel angle profile as horizontal members and steel angle profile as diagonal members. It has been shown from the test that the strength capacity of steel truss coupling beam specimens can not reach ultimate load because of inelastic buckling. Experimental results show that steel truss coupling beam can have fairly well behaviour under cyclic loading. By enlarging the dimension of horizontal members and diagonal members without increasing the thickness of profile , the strength capacity of all coupling beam specimen will have different behaviour. The result shows that the specimen with larger dimension of profile exhibits slightly raising of strength capacity than specimen with smaller dimension. The envelope curve decrease gradually which represent the specimens have well performance in terms of dissipation energy. More over, increasing appropriate dimension of diagonal and horizontal members for steel truss coupling beam with shearwalls can determine and classify the structural performance level of structure.

Keywords: Coupling beam, Steel truss, Angle steel profile, Strength capacity

1. INTRODUCTION

A coupling beam works as a link beam between two shear walls namely coupled shearwall which can absorb more seicmic energy and attain plastic hinge mechanism before coupled shearwalls yield when an earthquake happens. According to the researchs, the structural strength of coupling beams can affect the behaviour of coupled shearwall. Paulay [1] described that the failure mechanism of coupling beam with small span to depth ratio is different with regular concrete beam. Previous experimental studies suggested the use of diagonally bars for reinforcing of coupling beam to resist lateral loading. Generally, the conventional coupling beam or namely diagonally reinforced concrete coupling beam can be defined as coupling beam with used a group of diagonal reinforcement as main bars that confined with transverse bars and reinforced concrete for lower span to depth ratio. Moreover, Indonesian building code SNI 2847:2013 [2] also suggests to use diagonal reinforcement for coupling beam with span to depth ratio less than two. Although many codes offer an alternatives reinforcements, but all configuration still difficult to construct.

Steel truss coupling beam is a reliable alternative for replacing the conventional coupling beam. Previous studies [3,4,5] investigated the behaviour of steel coupling beam on solid web steel and the experimental results showed that steel coupling beams indicate well behaviour in stiffness, energy dissipation and strength capacity. Moreover, cyclic behavior of very short shear link and replaceable steel coupling beam also reported by [6,7]. The results indicated that a short shear link and replaceable steel coupling beams can provide stable hysteretic behaviour and ductile under cyclic loading. Furthermore, Lin et al [8] investigates steel truss coupling beam with opening that using T-Stub chord members and angle web members. The experimental analysis indicates that steel truss coupling beam also represents good performance in terms of ductility and energy dissipation.

Based on the previous studies, this research puts forward the steel truss coupling beam that assembled from double steel angle profile as horizontal members and steel angle as diagonal members. Experimental test of steel truss coupling beams under lateral loading was described in this research in order to investigate the behaviour of steel truss coupling beams.

2. METHODS

2.1 Design of Specimen

The specimen of steel truss coupling beams are created considering several factors such as horizontal and diagonal members contribution. The strength capacity of steel truss coupling beam is provided by double steel angle profile as horizontal members and a steel angle profile as diagonal members.

The relation ship between flexure and shear according Fig.1 can be obtained by Eq.(1). The horizontal force component (F_h) can be calculated by using Eq.(2).

$$V_u = \frac{2M_u}{l_n} \quad (1)$$

$$F_h = \frac{M_u}{h} \quad (2)$$

where V_u = shear capacity of coupling beam, l_n = coupling beam clear span, M_u = ultimate flexural strength and h = the height of coupling beam.

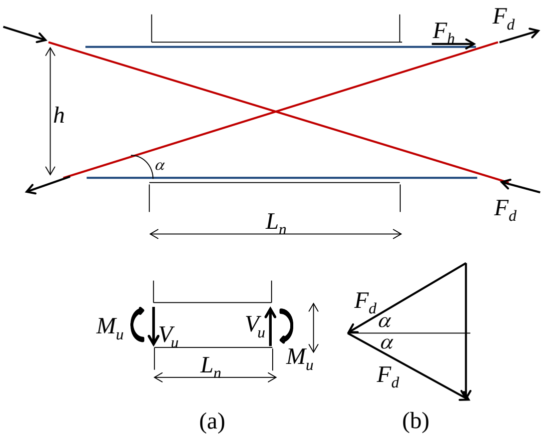


Fig. 1. Relationship between shear and flexure of coupling beam (a) external actions, (b) internal forces

The diagonal force contribution (F_d) can be calculated by Eq.(3)

$$F_d = \frac{V_u}{2\sin\alpha} = \frac{M_u}{l\sin\alpha} \quad (3)$$

From the above of equations, thea area of diagonal members A_d and horizontal members A_h can be created using Eqs.(4) and (5) if buckling is neglected.

$$A_d = \frac{F_d}{f_y} \quad (4)$$

$$A_h = \frac{F_h}{f_y} \quad (5)$$

2.2 Detail of Specimens

In this experiment, the steel truss coupling beams were tested under lateral cyclic loading to evaluate behaviour of steel truss coupling beams. The specimens consisted of scaled steel truss coupling beams and two stiff reinforced concrete member as structural walls. Prototype structure was adopted from previous research [9] and the coupling beam shear force that estimated from frame analysis according to [10] were chosen to be the models with scale of 1:2.5 as specimens of the coupling beams. The serial numbers of specimens were STCB 1 and STCB 2. STCB 1 is a specimen of steel truss coupling beam with the use of 2L.30x30x3 for horizontal members and L.30x30x3 for diagonal members. STCB 2 is a specimen of steel truss coupling beam with 2L.35x35x3 as horizontal members and L.35x35x3 as diagonal members. The span to depth ratios of specimens is 1.78 for ensuring a shear behaviour mechanism for evaluating the seismic response of steel truss coupling beam that designed using the area of horizontal and diagonal members. Detailed configuration dimensions of steel truss coupling beams are presented in Figs.2 and 3, see also Table 1.

Table 1. Detail of specimens STCB 1 and STCB 2

Specimens	Span to depth ratio	Horizontal Member	Diagonal Member
STCB 1	1.78	2L.30x30x3	L.30x30x3
STCB 2	1.78	2L.35x35x3	L.35x35x3

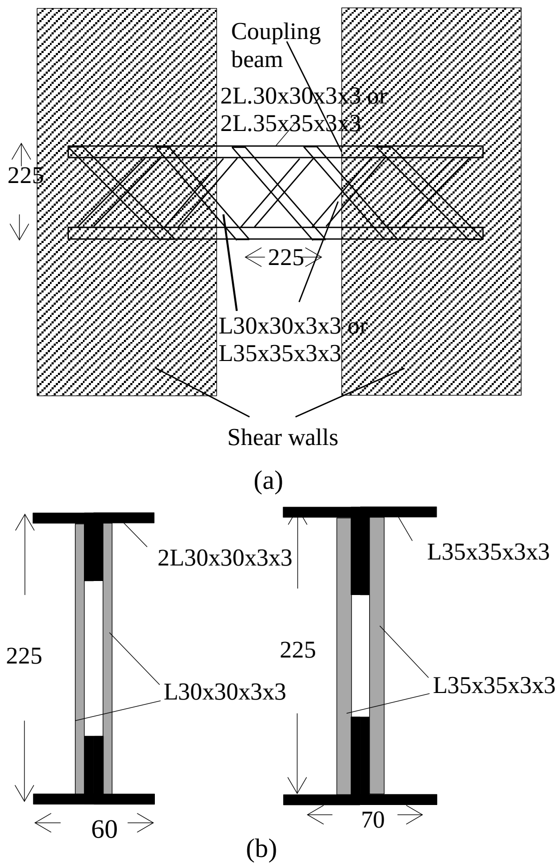


Fig. 2. Cross section of specimens (a). STCB 1, (b) STCB 2

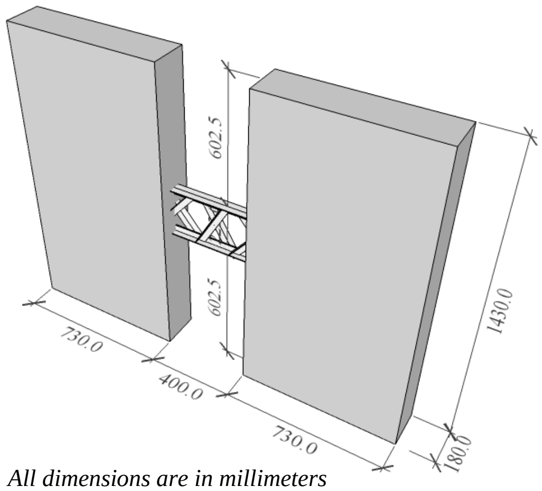


Fig. 3. 3D sketch of specimen of steel truss coupling beam and shear walls

2.3 Mechanical Properties

The mechanical properties of steel of specimens is presented in Table 2.

Table 2. Mechanical Properties of Specimens

Steel types	Steel Angle L.30x30x3	Steel Angle L.35x35x3
Yield Strength (MPa)	356.2	390.5
Ultimate Strength (MPa)	502.0	536.4

2.4 Test Set up and Loading History

Experimental testing was conducted in Structural Laboratorium in Civil and Environmental Engineering Department of Gadjah Mada University. Lateral load was produced by an actuator that was fastened to steel loading frame. Figure 4 depicts the detail of set up test of specimens that based on previous research [11].

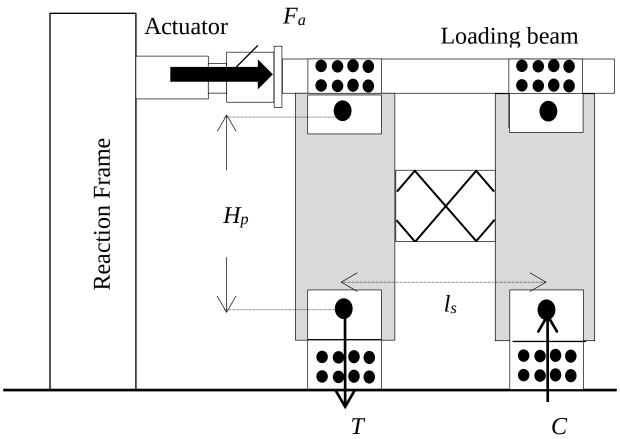


Fig. 4. Schematic Test Set Up

As illustrated in Fig.4, the relationship between actuator load (F_a) and shear force on the coupling beam (V_{cb}) can be simulated by Eq.(6) and Eq.(7)

$$F_a H_p = T l_s \tag{6}$$

$$\frac{F_a H_p}{l_s} = V_{cb} \tag{7}$$

where T = tension force that created in wall sections. The dimension of structural wall for all specimens were determined to be 143x73 cm. H_p can be defined as distance between top and bottom support of test set up and was measured to be 117.5 cm. Furthermore, l_s was chosen to be 113 cm and it can be explained as distance between the central of two wall section. Finally, the formulation to estimate shear force on the coupling beam can be described by Eq.(8).

$$1.04 F_a = V_{cb} \tag{8}$$

A quasi static lateral load with increasing displacement amplitudes was applied in this specimens. The loading was based on displacement control according to ACI T-11-01 [12] until the end of testing which shown in Fig.5. The series of test in loading history is intended to determine that horizontal load was increased gradually in step. Specimens was loaded and unloaded in the same displacement in each step. There were three loading cycles in each step.

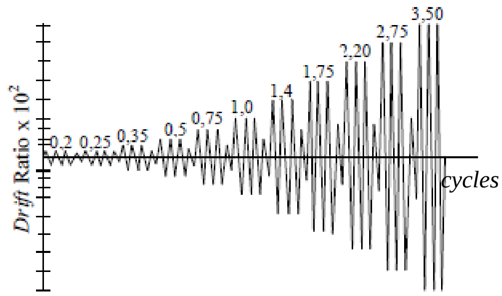


Fig. 5. Loading History of Specimen [12]

3. RESULT AND DISCUSSION

3.1 Diagonal Force Capacity

The diagonal and horizontal forces of both specimens (STCB 1 and STCB 2) were calculated according to Eqs.2 and 3. Meanwhile, the capacity of diagonal compressive strength determined by the buckling of steel angle profile according to SNI 1729: 2015 [13] as specification for structural steel building and the guideline in Indonesia which refers to AISC 2010 [14] . Diagonal compressive strength of profile can be classified as nonslender element and slender element section. Buckling failure of members without slender element can be calculated Eqs 9 until 11.

$$P_n = F_{cr} A_g \tag{9}$$

$$\frac{Kl}{r} \leq 4.71\sqrt{\frac{E}{f_y}}\left(or\,\frac{f_y}{F_e} \leq 2.25\right)$$

$$F_{cr} = \left[0.658^{\frac{f_y}{F_e}}\right] \tag{10}$$

$$\frac{Kl}{r} > 4.71\sqrt{\frac{E}{f_y}}\left(or\,\frac{f_y}{F_e} > 2.25\right)$$

$$F_{cr} = 0.877 F_e \tag{11}$$

where P_n = the nominal compressive strength / the capacity of diagonal member (kN), F_{cr} = the critical stress (MPa), f_y = yield stress of steel (MPa), F_e = elastic buckling stress (MPa) determined according to elastic buckling analysis by Eq.12.

$$F_e = \frac{\pi^2 E}{\left(\frac{Kl}{r}\right)^2} \tag{12}$$

where K= effective length factor, l = length of member (mm) and r = radius of giration (mm). Effective slender ratio Kl/r for steel angle profile can be determined in accordance with section E-5 [13].

Moreover, the diagonal force for members with slender element should be corrected by net reduction factor, $Q = Q_s Q_a$, which can be written by Eqs. 13 and 14.

$$\frac{Kl}{r} \leq 4.71\sqrt{\frac{E}{Qf_y}}\left(or\,\frac{Qf_y}{F_e} \leq 2.25\right)$$

$$F_{cr} = Q\left[0.658^{\frac{Qf_y}{F_e}}\right] \tag{13}$$

$$\frac{Kl}{r} > 4.71\sqrt{\frac{E}{Qf_y}}\left(or\,\frac{Qf_y}{F_e} > 2.25\right)$$

$$F_{cr} = 0.877 F_e \tag{14}$$

where Q_s is net reduction factor for slender unstiffened element and Q_a is reduction factor for slender stiffened element. For steel angle profile that included as unstiffened slender element , $Q=Q_s(Q_a=1)$ and Q_s can be predicted according to Eqs 15 until 17.

$$\frac{b}{t} < 0.45\sqrt{\frac{E}{f_y}}, Q_s = 1 \tag{15}$$

$$0.45\sqrt{\frac{E}{f_y}} < \frac{b}{t} < 0.91\sqrt{\frac{E}{f_y}})$$

$$Q_s = 1.34 - 0.76\left(\frac{b}{t}\right)\sqrt{\frac{f_y}{E}} \tag{16}$$

$$\frac{b}{t} > 0.91\sqrt{\frac{E}{f_y}}) \quad , \quad Q_s = \frac{053E}{f_y\left(\frac{b}{t}\right)^2} \tag{17}$$

Table 3 shows the comparison of compressive strength of diagonal element based on analytical theory and experimental results, where V_{Dy} = shear force design of coupling beam, F_{Dy} = yield compressive strength for diagonal element, V_{cr} = critical shear force for coupling beam and F_{cr} = critical compressive strength for diagonal element.

Table 3. Comparison result strength capacity of steel truss coupling beams

Type of specimens	Theory (kN)				Eksperimental (kN)	
	V_{Dy}	F_{Dy}	V_{cr}	F_{cr} [11]	V_{cr}	F_{cr}
STCB 1	77.93	55.11	37.32	26.40	37.23	26.32
STCB 2	89.48	63.27	40.96	28.97	38.68	27.35

From Table 3, it can be concluded that the strength capacity of steel truss coupling beam specimens can not reach ultimate load because of inelastic buckling.

3.2 Failure Mechanism

At the beginning of loading, horizontal load was raised incrementally in accordance with the increasing of displacement . Failure mechanism of specimens were determined as buckling in the diagonal members that can be shown from visual observation . During the test, diagonal members were compressed and tensed alternately as the diagonal members buckled and get back in the original shape when unloaded.

Specimen STCB 1 exhibited buckling failure mechanism that can be pointed by buckling almost of diagonal members. and in the next step of loading after buckling of diagonal members was substansial, horizontal members also started buckling. Furthermore, in the final step of loading, the buckling of diagonal members were severe. From the observation, STCB 1 can be categorized by buckling failure mechanism. The ultimate strength that can be reached of specimen STCB 1 was 37.23 kN at drift ratio maximum 1.0% . On the other hand, the failure mechanism of STCB 2 slightly different with STCB 1. In the early of loading, STCB 2 also indicated buckling on the both of diagonal members. At the advanced of loading, the horizontal members indicated slightly bending but still in fairly well condition. Finally, the buckling of diagonal members were severe on the end of test and can be drawn as inelastic buckling failure mechanism. The ultimate strength of STCB 2 is 38.68 kN at drift ratio maximum 0.5%.

The failure pattern of both specimens were governed by buckling mechanism because the diagonal members collapsed before horizontal members. More over, it can be drawn that the enlarging dimension of profile without adding the thickness of profile exhibited slightly enhancement of coupling beam capacity . Finally, the specimens cannot reach the shear force design. Failure condition of test specimen in the end of testing was described in Fig.6.

(a)

(b)

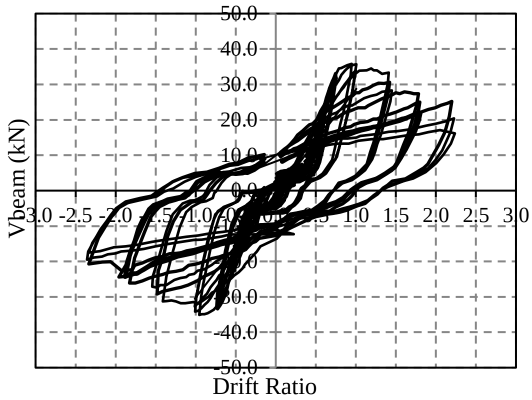
Fig. 6. Coupling beams after test
(a) STCB 1, (b) STCB 2

3.3 Hysteretic Performance

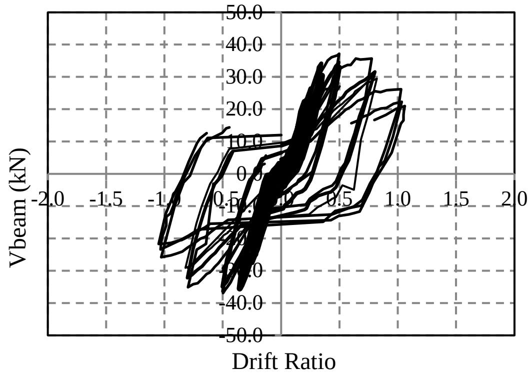
The hysteretic performance of specimens are shown in Fig.7, which shows the relationship between load and displacement of specimens of shearwall with steel truss coupling beams

In the early stage of loading, the shape of hysteretic curve tend to be similar in each step displacement. It means that specimens still in the elastic region that can be indicated with small deformation of coupling beams. When diagonal member was buckling , the shape of hysteretic curve also changed with the area of curve become larger than inital condition.

Fig.7 shown that enlarging the dimension of horizontal and diagonal members of steel truss without adjusted the thickness of profile can slightly raise the strength capacity of steel truss, but can improve the stiffness of steel truss coupling beam.



(a)



(b)

Fig. 7. Hysteretic Curve of Coupling Beams
(a) STCB 1, (b) STCB 2

3.4 Analysis of Envelope Curves

According to ASTM E 2126-02a [15], Equivalent Energy Elastic Plastic Curve (EEEPC) can be used for estimating the performance parameters of specimens that can be shown in Fig. 8. Yield load and elastic stiffness of specimens can be predicted from EEEPC. Elastic stiffness can be calculated by Eq.18, where P_{peak} = the maximum load and $\Delta_{0.4Peak}$ = displacement when the load equal with 40% maximum load.

$$k_e = \frac{0.4P_{peak}}{\Delta_{0.4P_{peak}}} \tag{18}$$

The yield load of specimen can be determined by Eq.19, where P_{yield} is the yield load of specimen, A

defined as the area under load displacement curve from zero to ultimate displacement and Δu is displacement when structural bearing capacity decline to 80% ultimate displacement.

$$P_{yield} = \left(\Delta_u - \sqrt{\Delta_u{}^2 - \frac{2A}{k_e}} \right) k_e \qquad (19)$$

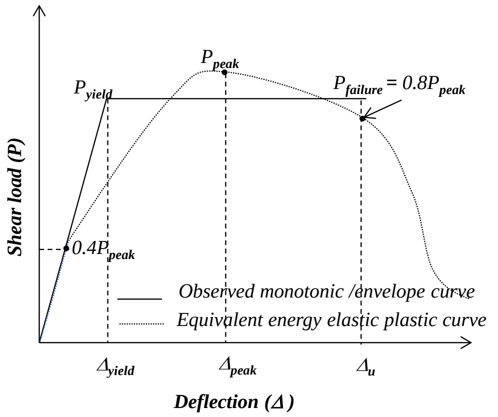


Fig. 8. EEEPC Curve of specimens [15]

Table 4 and Table 5 present yield loads, yield displacements, ultimate loads, ultimate displacements, failure loads and failure displacements that can be estimated when the load decline to 80% ultimate loads based on Equivalent Energy Elastic Plastic Curve (EEEPC). All specimens for tension loading and compression loading.

Table 4. Strength capacity of specimens steel truss coupling beams on the tension loading

Criteria		Code of specimens	
		STCB 1	STCB 2
Yield	V_{beam} (kN)	26.04	32.06
	Disp (mm)	10.35	4.06
Ultimate	V_{beam} (kN)	37.23	38.68
	Disp (mm)	12.11	6.37
Failure	V_{beam} (kN)	29.78	30.95
	Disp (mm)	21.82	11.95

Table 5. Strength capacity of specimen steel truss coupling beams on the compression loading

Criteria		Code of specimens	
		STCB 1	STCB 2
Yield	V_{beam} (N)	28.42	32.78
	Disp (mm)	9.57	3.97
Ultimate	V_{beam} (N)	36.50	38.37
	Disp (mm)	12.25	6.37
Failure	V_{beam} (N)	29.20	30.70
	Disp (mm)	21.35	11.98

Figure 9 shows the backbone curve of specimens. Backbone curve describes the relationship between strength capacity and drift ratio of specimen that taken from the first cycle of each drift of cyclic loading history of specimen. From the Fig.9, it can be described that the envelope curves decrease gradually which represent the specimens have well performance in terms of dissipation energy of specimens.

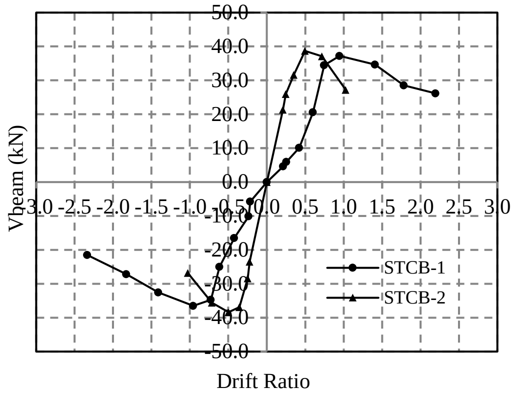


Fig. 9. Backbone curve of specimens steel truss coupling beams

3.5 Ductility Factor

The ductility factor μ is normally calculated from $\mu=\delta_u/\delta_y$,where δ_u is the ultimate lateral displacement when structural bearing capacity decline to 80% ultimate bearing capacity, δ_y is yield lateral displacement. How ever proposed a method to calculate the ductility factor according to research by Satyarno [16], can be expressed by Eq.20.

$$\mu_u = \frac{T_{eff}^2}{T_1^2} \qquad (20)$$

$\boldsymbol{T_1}$ is the elastic fundamental period of the structure that can be calculated by Eq.21 and $\boldsymbol{T^*_{eff}}$ is defined as the effective period of the structure that can be estimated by Eq.22.

$$T_1 = 2\pi\sqrt{\frac{M^*}{K^*_{elastic}}} \qquad (21)$$

$$T^*_{eff} = 2\pi\sqrt{\frac{M^*}{K^*_{eff}}} \qquad (22)$$

$\boldsymbol{M^*}$, $\boldsymbol{K^*_{elastic}}$ and $\boldsymbol{K^*_{eff}}$ are the equivalent mass, elastic stiffness and equivalent effective stiffness respectively. Substituting the Eqs. 21 an 22 into Eq. 20, ductility factor of structure can be expressed by Eq.23.

$$\mu_u = \frac{K_{elastic}}{K_{eff}} \qquad (23)$$

Table 6 provides the calculated ductility factor of specimens with using Eq. 23.

Table 6. Ductility factor of specimens

Code of specimens	Ductility Factor	
	Compression load	Tension load
STCB 1	2.02	2.20
STCB 2	3.05	3.22

According to this calculation, the ductility factor in the compression load for STCB 1 was 2.02 and for tension load was 2.20. The ductility factor of STCB 2 for compression and tension load were 3.05 and 3.22 respectively. In accordance with FEMA 306 [17], all specimen of steel truss coupling beams can be classified as moderate ductility.

3.6 Dissipation Energy

In order to measure the energy dissipation of specimens, Equivalent Viscous Damping Ratio (EVDR) was calculated for all specimen of coupling beams. A higher value of EVDR means that the specimen has greater ability of dissipation energy. Definition of EVDR can be shown by Fig 10 and Eq.24.

$$EVDR = \frac{HE}{2\pi PE} \tag{24}$$

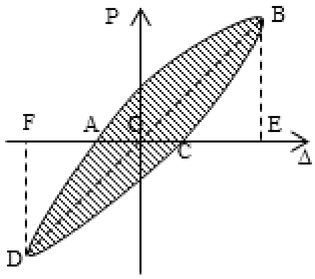


Fig. 10. Definition of Equivalent Viscous Damping Ratio [8]

where *HE* is the ability of structure to save energy that can be predicted with the loop area of ABC and ACD . *PE* is energy potential of structure that can be estimated with the triangle area of OBE and OFD. The curve in Fig.11 shows the relationship between EVDR and the displacement for specimens. Specimen STCB 1 and STCB 2 show the raising level of dissipation energy with increased displacement. The value of Equivalent Viscous Damping Ratio (EVDR) of STCB1 is smaller than STCB 2 at the same displacement.

According to Paz [18], the damping ratio of structural system is usually less than 20% of critical damping. It means that specimens of steel truss coupling beams have good energy dissipation capacity.

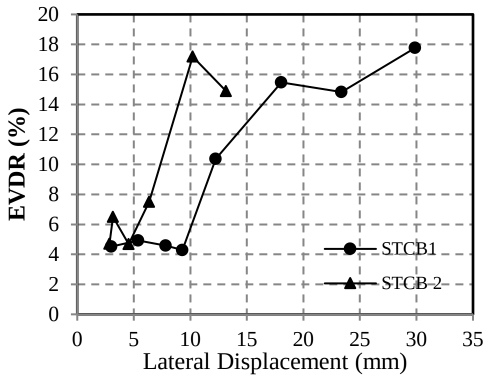


Fig. 11. Energy Dissipation Ratio of Specimens

3.7 Structural Performance Level

FEMA 356 [19] defines three level of structural performance for determining the condition of structure. These are immediate occupancy (IO), life safety (LS) and collapse prevention (CP). Immediate occupancy (IO) can be explained as the post earthquake damage with minimal structural damage has developed. More over, Life safety (LS) is defined as the post earthquake damage with significant structural damage has occured. Several component and element structure are damage. Collapse prevention (CP) is defined as the post earthquake damage state with the structure is on the close to partial or total collapse. Substansial damage of structure such as degradation stiffness and large permanent lateral deformation of structure were occured.

Table 7 shows structural performance level for concrete walls with coupling beam according to FEMA 356 [19]. Table 8 describes the state of structural performance of specimens.

Table 7. Structural performance levels for concrete walls with coupling beam [19]

Type	Structural performance levels		
	Collapse Prevention (CP)	Life Safety (LS)	Immediate Occupancy (IO)
Drifts	2% transient or permanent	1% transient, 0.5% permanent	0.5% transient; negligible permanent

Table 8. Structural performance levels (Experimental result)

Criteria	STCB-1	STCB-2
$P_{(Lateral\ Load)}$ (kN)	35.80	37.20
$V_{coupling\ beam}$ (kN)	37.23	38.68
Drift Ratio (%)	1.0	0.5
Structural performance levels	Life safety (LS)	Immediate Occupancy (IO)

Table 8 shows that structural performance level of specimen of STCB 1 can be categorized as Life Safety (LS) level with drift ratio maximum at 1.0%. Meanwhile, specimen of STCB 2 is classified as Immediate Occupancy (IO) level with drift ratio maximum at 0.5% .

4. CONCLUSION

This paper focused on the steel truss coupling beams in coupled shearwall. The following conclusion were drawn :

1. Enlarging the dimension of horizontal and diagonal members of steel truss without increasing the thickness of profile exhibited slightly enhancement of strength capacity of steel truss coupling beam.
2. The ductility factor of specimens steel truss coupling beams can be classified as moderate ductility .
3. From the backbone curve and the calculation of equivalent viscous damping ratio , specimens steel truss coupling beams have well performance of energy dissipation capacity.
4. Increasing appropriate dimension of diagonal and horizontal members for steel truss coupling beam with shearwalls can determine and classify the structural performance level of system.

5. ACKNOWLEDGEMENT

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