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Analysis and Design of Shear Wall Coupling Beam using Hybrid Steel Truss Encased in Reinforced Mortar

Nursiah Chairunnisa [a]*, Iman Satyarno [b], Muslikh [b], Akhmad Aminullah [b]

[a]Ph.D Student of Civil and Environmental Engineering Department of Gadjah Mada University, 55281,Indonesia
[b]Civil and Environmental Engineering Department of Gadjah Mada University, 55281,Indonesia

Abstract

Shear wall coupling beam using hybrid steel truss encased in reinforced mortar is proposed in this paper as an alternative method of that conventional reinforced concrete coupling beam. The application of steel truss is to substitute the need of longitudinal, transversal, and diagonal steel reinforcement in the reinforced concrete shear wall coupling beam which is commonly very difficult to install on site due to the crowded of steel bars reinforcement. Meanwhile the application of encased reinforced mortar is mainly to prevent the steel truss from premature buckling and at the same time may also to increase the shear and flexural capacity. Only analytical and design examples of various arrangement of steel truss and encased mortar are given in this paper as the laboratory tests are still under the way. The examples use typical reinforced concrete coupling beam with span to depth ratio that requires conventional diagonally reinforcement. Various design using steel truss coupling beam with and without buckling consideration, steel truss coupling beam encased in mortar only, and steel truss coupling beam encased in reinforced mortar as alternative design are discussed. It is found that the alternative method gives the most reliable alternative.

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Keywords: *Hybrid; truss; coupling beam; mortar; shear capacity*

1. Introduction

Hybrid structural system is defined as structural system that consist of combination between structural steel and reinforced concrete (RC) member. Nowadays, these system is quite common in many countries and one of them is hybrid shear wall coupling beam. Hybrid shear wall coupling beam is an alternative method of that conventional reinforced concrete coupling beam, diagonal reinforced concrete coupling beam, steel coupling beam and steel-concrete coupling beam. Hybrid shear wall coupling beam consisting of steel truss as a structural steel and encased

* Corresponding author. Tel.: +62-274-545675; +628125108541; fax: +62-274-545676;.
E-mail address: chairunnisaftunlam@gmail.com; iman@tsipil.ugm.ac.id; nursiah.chairunnisa@mail.ugm.ac.id

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in reinforced mortar as a reinforced concrete (RC) member. The application of steel truss in this method is to substitute the need of longitudinal, transversal, and diagonal steel reinforcement in the reinforced concrete shear wall coupling beam which is commonly very difficult to install on site due to the crowded of steel bars reinforcement. Meanwhile the application of encased reinforced mortar is mainly to prevent the steel truss from premature buckling and at the same time may also to increase the shear and flexural capacity of the coupling beam. Analytical analysis in hybrid shear wall coupling beam is separately between steel truss analysis and calculation of encased in reinforced mortar.

The failure mechanism of coupling beam greatly affects the efficiency of the coupled shear wall for resisting lateral load. Well designed of coupling beam can enhance ductility, strength and stiffness of the coupled shear wall compared to the individual wall. More over, for ensuring ductile response for the coupled shear wall system, the various design code requires that deep coupling beam will be designed for shear with small span-to-depth ratio and confined with diagonal bars [1]. Previous study suggests that a hybrid steel truss is an alternative method of coupling beam [2].

Only analytical and design examples of various typically type of coupling beams including various arrangement of steel truss and encased mortar are given in this paper as the laboratory tests are still under the way. The examples use typical reinforced concrete coupling beam with span-to-depth ratio that requires conventional diagonally reinforcement . Various design using steel truss coupling beam with and without buckling consideration, steel truss coupling beam encased in mortar only, and steel truss coupling beam encased in reinforced mortar as alternative design of that conventional design are discussed.

2. Analysis Model of Coupled Shear wall with reinforced concrete coupling beam.

Paulay and Priestley [3] designed coupled shear wall structure with span-to-depth ratio are 1.25 and 0.67. Overall dimensions, assumed member sizes are shown in Table 1.

Table 1. Schedule of proposed wall and beam dimensions and material properties [3]

No	Level	Width (b)	Depth (h)	Thickness (t)	Material Properties
1	10 -11	250	800	200	Beam reinforcement f_y = 275 MPa
2	8 – 9	300	800	250	Wall reinforcement f_y = 380 MPa
3	3-7	350	800	300	Hoop or tie reinforcement f_y = 275 MPa
4	2	350	1500	350	Concrete f_c' = 30 MPa
					(above level 3) f_c' = 25 MPa

All dimensions are in millimetres

The design of coupled shear wall structure according to Paulay and Priestley [3] will be compared to various type of coupled shear wall model based on finite element method using Program SAP 2000 [4]. The coupled shear wall model with conventional reinforced concrete coupling beam be approached with various two-dimensional (planar) models that suitable for lateral load analysis of coupled shear wall system. These types can be divided into three element such as shell-shell element, shell-frame element and frame-frame element. Such models can be used to predict beam and wall design forces. The wall is divided into smaller elements that be shaped triangular, rectangular or quadrilateral. Second type of coupled shear wall model can be approached with shell – frame element . In this model, each shear wall is replaced by an idealized shell element and coupling beam between shear wall is assumed as idealized frame element with rigid body at the interface of shear wall and coupling beam for ensuring the stiffness. More over, the equivalent frame model is the last type of coupled shearwall model. These model was developed by Clough et al. [5], Candy [6] and MacLeod [7] for the analysis of two dimensional coupled shear wall structures. This model consisting of idealized frame structure for both shear wall and coupling beam. Fig.1 depicts three types of coupled shear wall models using shell-shell element, shell-frame element and frame element.

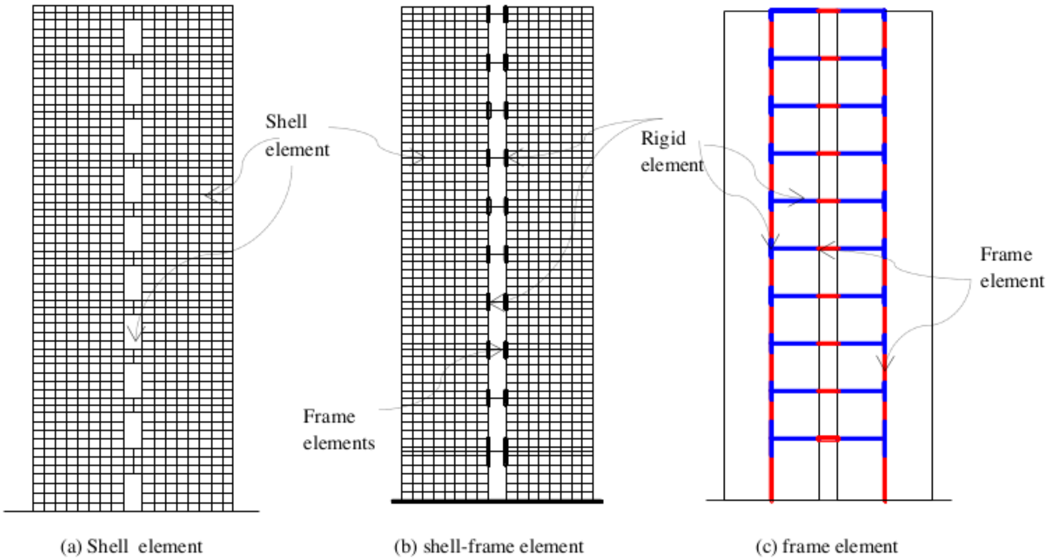

Fig. 1. Three types of coupled shear wall models

The results of beam shear forces and axial forces in wall from that three types of coupled shearwall models are compared to the design of coupled shear wall system according to Paulay and Priestley [3] and have been tabulated in Table 2 and Fig.2.

Table 2. Comparison beam shear forces and axial forces in wall from various type of coupled shear wall models to [3]

Number of Story	Beam Shear Force (kN)				Axial Forces in Wall (kN)			
	Paulay & Priestley [3]	Shell-Shell	Shell-Frame	Frame-Frame	Paulay & Priestley [3]	Shell-Shell	Shell-Frame	Frame-Frame
8	456	497.77	494.49	422.07	1350	1361.69	1380.98	1188.90
7	592	613.9	611.54	555.03	1944	1975.59	1992.22	1743.92
6	644	685.78	677.23	609.57	2568	2661.37	2669.75	2353.50
5	676	733.58	718.05	647.37	3264	3394.96	3387,80	3000.87
4	669	749.02	724.03	643.16	3933	4143.94	4111.82	3644.03
3	592	701.96	666.32	550.56	4525	4845.94	4778.15	4194.59
2	908	983.97	991.56	1212.17	5433	5829.91	5769.71	5406.75

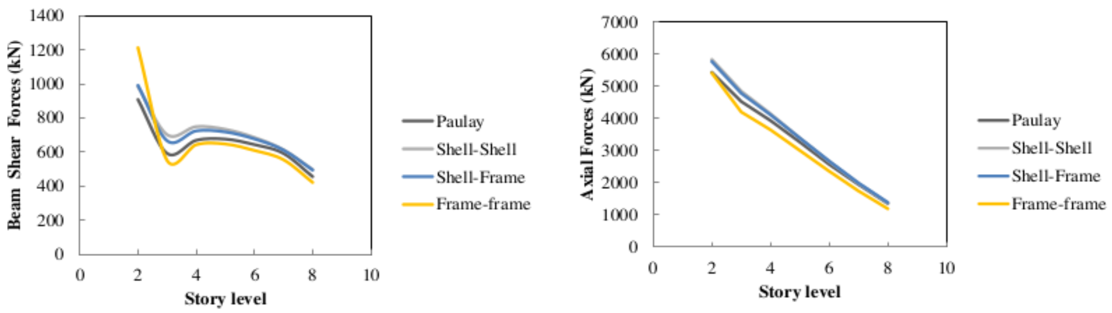

Fig. 2 (a). A comparison beam shear forces from [3] and models, (b) A comparison axial forces from [3] and models

Coupled shear wall model with idealized shell element as a bench mark for other models. It found that, the error percentage axial wall forces ,wall shear forces and beam shear of second and third models to first model is given in Table 3.

Table 3. Error percentage forces of second and third models to first models of coupled shear wall

Number of story	Axial Wall Forces (%)		Wall Shear Forces (%)				Beam Shear Forces (%)	
	Shell-Frame	Frame-Frame	Shell-Frame		Frame-Frame		Shell-Frame	Frame-Frame
			Left	Right	Left	Right		
8	1.42	-12.69	-0.03	0.03	4.27	-3.92	-0.66	-15.21
7	0.84	-11.73	0.00	0.00	2.08	-1.96	-0.38	-9.59
6	0.31	-11.57	0.00	0.00	1.36	-1.3	-1.25	-11.11
5	-0.21	-11.61	0.00	0.00	1.26	-1.22	-2.12	-11.75
4	-0.78	-12.06	0.01	-0.01	1.56	-1.53	-3.34	-14.13
3	-1.40	-13.44	0.01	-0.01	1.97	-1.97	-5.08	-21.57
2	-1.03	-7.26	-0.03	-0.04	1.09	-1.11	0.77	23.19

According to Finite Element Method analysis using Program SAP 2000 [4], it found that all type of models can predict similar outcomes, such as beam shear , axial forces and wall shear forces. it can be concluded that two dimensional shell –frame model and an equivalent frame model are appropriate models for analysis coupled shear wall models. The beam shear force was used for designing of coupling beam.

3. Design of coupling beams

Depending on the span-to-depth ratio, coupling beams can be designed differently, namely flexural failure mode and shear failure mode. There are various type of reinforcement in coupling beams desribed as follows.

3.1 Conventional reinforcement

Conventional reinforcement in reinforced concrete coupling beam is defined as coupling beams that consist of longitudinal bars, concrete dan shear strirrups. Shear capacity of conventional reinforced concrete coupling beams can be predicted according Paulay [8].

3.2 Diagonal reinforcement

Diagonal reinforced concrete coupling beam is defined as coupling beam that consist of longitudinal bars, diagonal reinforcements, concrete and shear strirrups. For beams with span-to-depth ratio less than two, two grups of diagonal bars that consist of minimum of four bars per diagonal are required for reinforcing the coupling beam. According to [1] tension and compresion stresses of diagonal coupling beam can be predicted as

$$T_u = C_u = A_s f_y \tag{1}$$

More over, shear capacity of diagonal coupling beams can be calculated as

$$V_u = 2T_u sin\alpha \tag{2}$$

In general, the area of diagonal reinforcement required is

$$A_{vd} = \frac{V_u}{2f_y sin\alpha} \tag{3}$$

3.3 steel truss coupling beam and hybrid steel truss

The application of steel truss in this method is to substitute the need of longitudinal, transversal, and diagonal steel reinforcement in the reinforced concrete shear wall coupling beam which is commonly very difficult to install on site due to the crowded of steel bars reinforcement. The steel truss is considered to contribute to the flexural and shear capacity. The steel truss coupling beams consist of T-profile steel and angle steel . The steel truss coupling beam is designed considering the factors of longitudinal and diagonal members. The relationship between flexural and shear capacity is shown as

$$V_u = \frac{2M_u}{L_n} \quad (4)$$

The horizontal force component (F_h) is calculated by

$$F_h = \frac{M_u}{h} \quad (5)$$

Hence, the area of longitudinal members requred can be written as

$$A_h = \frac{F_h}{f_y} \quad (6)$$

The diagonal force component (F_d) is designed by

$$F_d = \frac{V_u}{sin\alpha} = \frac{2M_u}{L_n sin\alpha} \quad (7)$$

The flexural capacity provided by longitudinal member such as T-profile is

$$M_u = M_{st} = A_{st} f_y h \quad (8)$$

The shear resistance be obtained by diagonal member such as angle steel is

$$V_{st} = F_d sin\alpha \quad (9)$$

The area of diagonal members required can be written as

$$A_d = \frac{F_d}{f_y} \quad (10)$$

Additionally, design of steel truss coupling beam is divided into two types such as with and without buckling consideration. The geometric dimensions of longitudinal and diagonal members of diagonal coupling beams, steel truss coupling beams are separately shown in Table 4.

Table 4. The geometric dimension of various design of coupling beams

No	Story	Span to depth ratio	Diagonal reinforced coupling beam	Steel truss coupling beam without buckling consideration		Steel truss coupling beam with buckling consideration	
			Diagonal bars	T-profile dimension	Angle steel	T-profile dimension	Angle steel
1	11	1.25	4D16	T 75x75x7x5	L50x5	T124x124x8x5.5	L75x9
2	10	1.25	4D16	T 100x100x8x5.5	L65x8	T175x175x11x7	2L65x8
3	9	1.25	4D24	T124x124x8x5.5	L75x9	T175x175x11x7	2L65x8
4	8	1.25	4D24	T150x150x9x6.5	L75x12	T100x200x12x8	2L75x9
5	7	1.25	4D24	T175x175x11x7	2L75x9	T100x200x12x8	2L75x12
6	6	1.25	4D24	T175x175x11x7	2L75x9	T100x200x12x8	2L75x12
7	5	1.25	4D24	T175x175x11x7	2L75x9	T100x200x12x8	2L75x12
8	4	1.25	4D24	T175x175x11x7	2L75x9	T100x200x12x8	2L75x9
9	3	1.25	4D24	T175x175x11x7	2L75x9	T175x175x11x7	2L75x9
10	2	1.25	4D28	T150x150x9x6.5	2L75x9	T175x175x11x7	2L75x9

3.4. Hybrid Steel truss coupling beam

The steel truss component will be covered by reinforced mortar, namely hybrid steel truss coupling beam. The application of encased reinforced mortar is mainly to prevent the steel truss from premature buckling and at the same time may also to increase the shear and flexural capacity of the coupling beam (Fig. 3). Steel truss and reinforced mortar are considered to contribute flexural and shear resistance. The flexural resistance is provided by longitudinal steel in reinforced mortar is

$$M_s = A_s f_y h \quad (11)$$

The total flexural resistance provided by hybrid steel truss is

$$M_T = M_s + M_{st} \quad (12)$$

The shear resistance of the section is provided by diagonal steel truss and reinforced mortar. The shear resistance contributed by reinforced mortar is

$$V_r = V_s + V_c = \frac{A_v f_y d}{s} + \frac{f_c b_w d}{6} \quad (13)$$

The total shear resistance provided by hybrid steel truss is

$$V_T = V_{st} + V_r \quad (14)$$

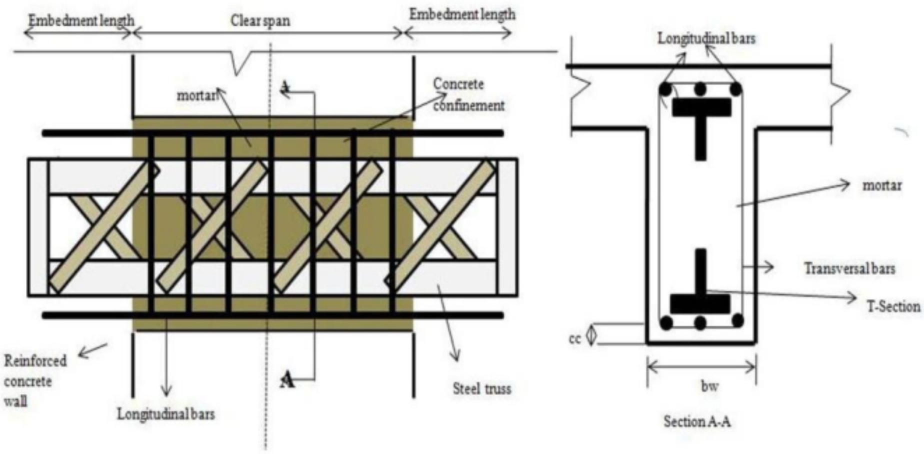

Fig. 3. Hybrid Steel Truss Encased in Reinforced Mortar (Chairunnisa et. al.,2014)

The variables needed for the design of all coupling beams are known. The span-to-depth ratio of coupling beam is 1.25 and 0.67. Water cement ratio 0.4 and 1:1 for water and sand ratio are used in mix design of mortar. Moreover *viscocrete-10* 1.5% from cement weight is applied for workability. The average compressive strength mortar is 45.74 MPa and modulus of elasticity is 26138.46 MPa [9]. From these known values, design of steel truss coupling beam encased mortar and hybrid steel truss coupling beam encased in reinforced mortar can be created. The objective for designing of steel truss coupling beam encased mortar is to study the influence of mortar in failure mechanism of beam, whereas design of hybrid steel truss encased in reinforced mortar is intended to prevent the premature buckling and to evaluate the enhancement of shear and flexural capacity. Table 5 shows the design of hybrid steel truss coupling beam for story -8.

Table 5. The design of hybrid steel truss coupling beam encased in reinforced mortar for story-8

Hybrid coupling beam				
Steel Truss		Reinforced mortar		
T Profile dimension	Steel Angle	Longitudinal bar diameter	Transversal bar diameter	Mortar (MPa)
T150x150x9x6.5	L 75x12	3D12	ϕ6-200	$f_c' = 45.74$

All dimensions are in millimetres

4. Modelling steel truss coupling beam in coupled shear wall system

Steel truss coupling beam in coupled shear wall can created as shell-frame element and frame-frame element . Both models of steel truss coupling beam in coupled shearwall systems are illustrated in Fig.4. Rigid bodies in interface of shear wall and steel coupling beam are created in shell-frame model and also frame model for ensuring stiffness of structures. The result of experimental study about seismic behaviour of steel truss coupling beam depicted that utilizing steel truss coupling beam provided good ductility and energy absorption [10]. Extensive studies about composite coupling beams such as steel concrete coupling beam [11,12,13,14,] conclude that steel coupling beam which encased in concrete provides an ability for preventing web and flange buckling and the usage of web stiffeners can be eliminated. In proposed method, for investigating hybrid steel truss coupling beam with encased mortar, shell-frame element model is used. In this paper, an attempt has been created to establish a model of hybrid steel truss to study the influence of mortar in steel coupling beam. Encased mortar in hybrid steel truss has been applied through the length of coupling beam.

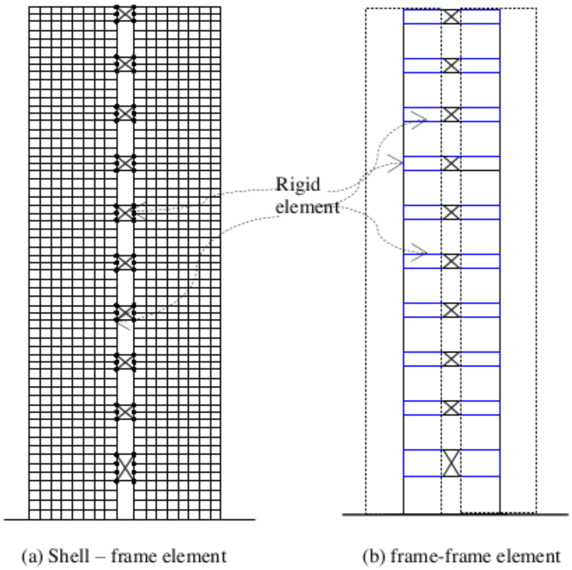

Fig. 4. Modelling Steel truss coupling beam in coupled shearwall

The finite element method result obtained that capacity ratio of T profile and an angle steel in hybrid steel truss coupling beam encased mortar significantly increase if compared to steel truss coupling beam. Furthermore, the dimension of T-profile as longitudinal members and an angle steel as diagonal members can be diminished for efficiency. The analysis depicted that the application of encased mortar in hybrid coupling beam model can restrain the steel truss from premature buckling and at the same time may also raise the flexural and shear capacity of the coupling beam. In this example analysis, the usage of diagonal members can be alleviated in hybrid steel truss encased mortar. Further more, a comparison of the joint displacements of the building structures for whole models is given in Fig.5.

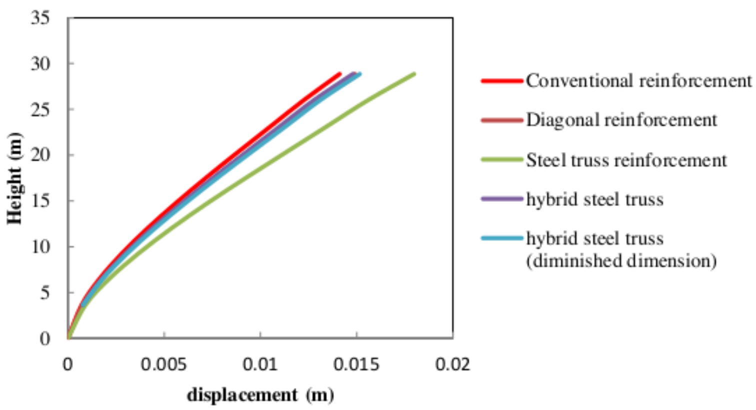

Fig. 5 A comparison of joint displacement for whole models

5. Conclusion

Based on analytical study with finite element method about analysis and design of shear wall coupling beam using hybrid steel truss encased in reinforced mortar, the following conclusion are drawn.

1. Two dimensional shell model, shell –frame model and an equivalent frame model are appropriate models for analysis finite element method for coupled shear wall models.
2. This analytical study has proposed and implemented a design of coupled shear wall using steel truss coupling beam encased mortar in Program SAP 2000 as a computer program. The model developed in this analytical study is a full scale model validated with the analysis coupled shear wall that was studied by Paulay and Priestley [3].
3. Nevertheless this models may still be refined, the proposed models which using application encased mortar in steel truss coupling beam in coupled shear wall gives the most reliable alternative design for substituting diagonal reinforced concrete coupling beams in coupled shear wall.
4. Steel truss coupling beam model based on an assumed rigid body in the interface between shear wall and coupling beam in coupling shear wall for ensuring stiffness in this area.
5. Profile steel dimension in hybrid steel truss encased mortar can be sharply declined with the application of encased mortar .

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