Various existing methods of coupling beams and a new alternative hybrid method

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Various existing methods of coupling beams and a new alternative hybrid method

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Abstract

The performance of various existing methods of coupling beams is summarized, including the disadvantages and advantages. According to previous researches reporting the utilization of diagonally reinforced concrete coupling beams for deep beam is essential and is the best solution to provide adequate ductility in coupling beams. However, diagonally reinforced concrete coupling beams have difficulties in practice due to congestion of reinforcement. With the purpose of simplifying construction, an alternative approach for the design of composite coupling beams will be suggested for further studies in experimental research through the use of hybrid component, which is a combination between ordinary reinforced concrete beams that will resist the flexure and steel trusses that will resist the development of high shear in the coupling beam. The proposed method will be compared to the performance of diagonal reinforced concrete coupling beams according to guideline SNI-2847:2013.

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Keywords: Diagonally reinforced concrete coupling beams; Steel coupling beams; Composite coupling beams; Hybrid coupling beams

1. Introduction

Indonesia is located in regions of high seismicity and therefore needs special notice in the construction medium of high risk building and usually rely on structural shear walls for lateral stiffness, strength and ductility. Coupling

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beams are defined as the beams that connect coupled shear wall and usually are required for providing access to elevators and stairwells. Coupling beams are created to restrain the development of high shear and also have sufficient ductility to dissipate the energy during an earthquake. It can be concluded that the behaviour of coupling beams affects the overall performance of coupled shear wall structures. Extensive research for over the past several decades about various methods of coupling beams, such as conventional and diagonal reinforced concrete coupling beams, steel coupling beams and also composite coupling beams were investigated, which will be described and reviewed in this paper. This is a huge influence and is useful for further studies of coupling beams.

2. Concrete coupling beams

Conventional Reinforced Concrete Coupling Beams (CRCCB) is defined as coupling beams that consist of longitudinal reinforcement, concrete and shear stirrups. The amount of shear reinforcement is higher than regular beams. In the past, researchers investigated short and deep coupling beams and showed that the behaviour of coupling beams is different than that of ordinary beams [1]. The experimental results reported that CRCCB specimens are vulnerable when subjected to cyclic loading. Paulay [1] also depicted that the failure of coupling beams with small length-to-depth ratios and conventional reinforced concrete coupling beams, was almost brittle and exhibited shear failure. Fig. 1 shows a typical layout of a conventional reinforced concrete coupling beam.

After the 1964 Alaska earthquake, several damages of conventional coupling beams indicated the inadequacy of coupling beams in shear capacity and weak seismic performance. Thereafter, extensive research on coupling beams was conducted to develop a new alternative for improved seismic performance, namely diagonally reinforced concrete coupling beams (DRCCB). Designs of DRCCB consist of longitudinal and diagonal reinforcement, shear stirrups, and concrete. The diagonal bar can be formed from single bars or a group of bars. Firstly, Paulay and Binney [2] investigated the use of a group of diagonal reinforcements confined with transverse bars for deep coupling beams. Fig. 2 depicts a model of diagonally reinforced concrete coupling beams (DRCCB). The research result suggested that a deep coupling beam collapses in a diagonal tension mode. Although this type of failure can be prevented by increasing shear stirrups, unfortunately under cyclic loading, a deep coupling beam also collapses in a shear-sliding mode. After the coupling beam test by [1], Santhakumar [3] reported testing two seven-storey, quarter-scale models of coupled wall under cyclic loading. The specimens consisted of conventional and diagonal reinforcement configuration of coupling beams. The experimental results showed that the failure mechanism of both types of coupling beams was due to sliding shear failure and buckling of diagonal bars. Other testing programs to investigate the behaviour of coupling beams under cyclic loading were conducted by researchers [4,5], who studied eight reinforced concrete coupling beams with span-to-depth ratios of 2.5 and 5.0 under reversed cyclic loading.

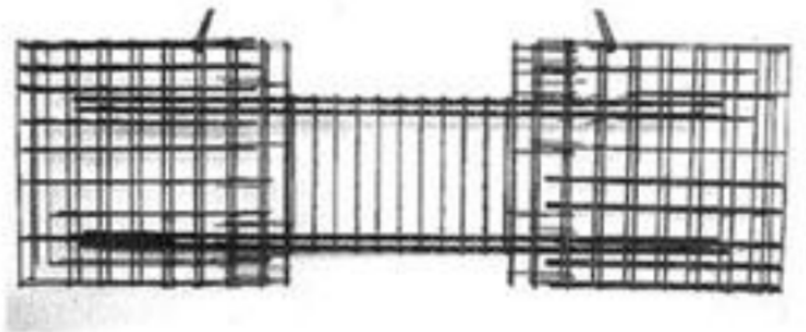

Fig.1. Typical Layout of Conventionally Reinforced Coupling Beam [1].

Fig.2.Typical Layout of diagonally Reinforced Coupling Beam [2].

Model of coupling beams that consists of three different reinforcement configurations i.e., conventional bars, diagonal reinforcements that close the beam-wall interface and with full-length diagonal reinforcement. The experiment depicts that CRCCB was limited by sliding shear failure close at the ends of the beam even though there were transverse reinforcements. Beams with diagonal bar in the hinge region, namely rhombic reinforcement configuration, could alleviate sliding shear failure mode but did not greatly enhance the coupling beams' performance. Based on tests, the last type of model with full-length diagonal bar described the best performance in ductility of coupling beams with small span-to-depth ratio. On the contrary, improvement in performance of the coupling beam (span-to-depth ratio 5.0) with the last type of reinforcement configuration was relatively small. Although DRCCB indicates well seismic performance, there are still some disadvantages. First, the use of a group of diagonal reinforcements can lead to an increase in beam width and larger walls. Second, closely spaced transverse stirrups around diagonal bars can cause difficulty in construction. On the other hand, Tassios et al. [5] performed similar investigation for alternative detailing of coupling beams under cyclic loading. Models consisting of coupling beams with a 1:2 scale, included five different reinforcement configurations with span-to-depth ratios of 1.0 and 1.66 (Fig. 3). Fig. 3(c) shows a rhombic configuration which uses supplementary bars for sliding resistance without improving the flexural capacity at the joints of the beam-walls. Fig. 3(d) and 3(e) contains full-length and cut-off dowels which were purposed to restrain a sliding failure mode. Test results reported that the rhombic reinforcement behaved better than the CRCCB specimen and has a less complicated configuration detailing than DRCCB. Thus, DRCCB performed with a better behaviour in hysteretic loops, resistance of shear and energy dissipation.

Galano and Vignoli [6] continued research of coupling beams by conducting tests on deep coupling beams with span-to-depth ratio of 1.5. Specimens containing short coupling beams with four reinforcement configurations that consisted of conventional schemes, diagonal bars without and with confining, and a rhombic configuration. Experimental results indicated that the beams with diagonal or rhombic layout showed better performance than conventional reinforcement. The rhombic layout was more effective than diagonal schemes in terms of ductility and strength. Furthermore, Kwan and Zhao [7] studied deep coupling beams subjected to load reversals (Fig. 4). Specimens contain conventional reinforced concrete coupling beams with span-to-depth ratio 1.17, 1.40, 1.75, and 2.00. The results showed displacement ductility that increased by increasing the aspect ratio. These beams exhibited displacement ductility values of 4.0, 4.3, 5.0, 5.0 and 6.0 respectively. Besides, this research also investigated a diagonally reinforced concrete coupling beam which aspect ratio 1.17. The beams exhibited displacement ductility value of 4.0 and characteristics of energy dissipation of DRCCB that were better than CRCCB. Naish [8] tested and modelled reinforced concrete coupling beams under cyclic loading for slender coupling beams with aspect ratio 2.4 and 3.3. The reinforcement configuration for an aspect ratio of 2.4 composed a diagonally reinforced concrete coupling beam with hoops according to ACI 318-05 and other specimens with full section confinement without hoops as a new detailing requirement in ACI 318-08.

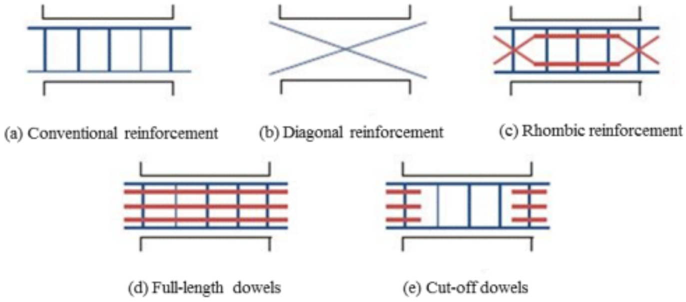

Fig.3.Reinforcement schemes [5].

Test outcomes depicted that new detailing in ACI 318-08 provided equivalent performance compared to coupling beams according to the old provision ACI 318-05 and that including a concrete slab, obtained a nominal increase in shear strength, approximately 20%. Although almost all researches indicated that diagonally reinforced coupling beams behave well under large displacement reversals, but diagonally reinforced concrete coupling beams have difficulties in practice due to congestion of reinforcement.

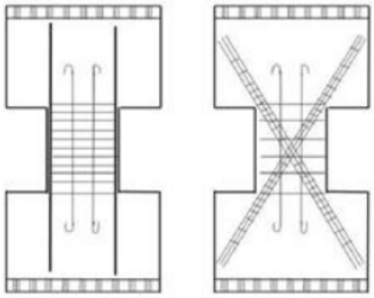

Fig.4.Typical Layout of diagonally Reinforced Coupling Beam [7].

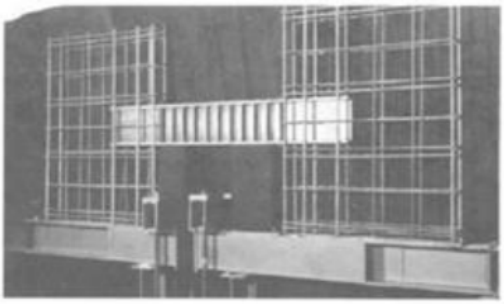

Fig.5.Typical Layout of steel Coupling Beam [9].

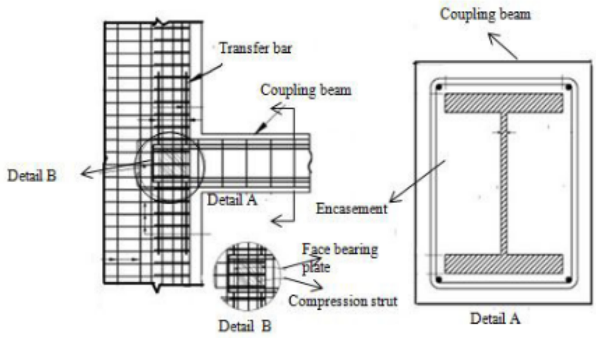

Fig.6. Specimen details of coupling beam [10].

3. Steel and composite coupling beams

To overcome the inadequacy of diagonally reinforced concrete coupling beams in construction and enhancing seismic performance of coupling beams, researchers attempted an alternative design with steel material because steel link beams provide characteristics with excellent ductility and energy dissipation. Harries et al. [9] conducted research using steel link beams which were embedded into reinforced concrete walls (Fig. 5). Specimens comprised of two full-scale coupling beams under cyclic loading. The test results reported that utilizing steel coupling beams provided excellent ductility and energy absorption. For small and medium span-to-depth ratios, performance of coupling beams was similar to link beams in eccentrically braced frames. Further investigation about steel and composite coupling beams were committed by Gong and Shahrooz [10] which suggested steel-concrete composite coupling beam as a feasible solution of coupling beams. The research focused on cyclic response of composite coupling beams and the effects of encasement that surrounds the coupling beams. Fig. 6 shows specimen details of coupling beams. The experimental result depicted that encasement around steel coupling beams enhanced their capability to prevent web buckling and the utilization of web stiffeners can be eliminated, and it also suggested re-evaluation of the old provision for adding the effect of encasement. On the other hand, Fortney [11] who suggested a viable alternative for coupling beams using beams with half-scale i.e. DRCCB, steel coupling beam (SCB), non-encased steel beams with a steel fuse link (FCB) and composite coupling beams (SPCB). Fig. 7 shows specimens of coupling beams [11]. The test result obtained showed that steel coupling beams' performance improved significantly in stiffness, capacity rotation and energy dissipation and SCB showed better performance compared to other specimens. However, FCB and DRCCB indicated relatively well behaviour in terms of stiffness and energy dissipation. Unfortunately, SPCB could not perform well because composite action between concrete and the steel plate could not be achieved.

Fig.7.Steel Fuse Coupling Beam (FCB) and Composite Coupling Beam (SPCB) [11].

The following research was continued by [12], which proposed the use of high-performance fibre reinforced cementitious composites (HPFRCC) in coupling beams with different reinforcement schemes. Coupling beam specimens with a 3/4 scale and an aspect ratio of 1.0 were tested, including a precast construction process that has been proposed for the HPFRCC coupling beams (Fig. 8). The structural performance of precast HPFRCC coupling beams under reversed cyclic loading showed a simplification of construction processes and the coupling beams provided adequate seismic behaviour. The use of HPFRCC materials allowed the reduction of the stirrups around the diagonal reinforcement. The test results demonstrated that the specimen with simplified diagonal reinforcement indicated higher performance in terms of shear strength and stiffness. However, HPFRCC materials have a superior performance under large displacement reversals compared to ordinary concrete.

Kuang et al. [13] demonstrated the use of steel-fibre reinforced concrete coupling beams (SFRC) with span-to-depth ratios of 1, 1.5 and 2 under monotonic loading (Fig. 9). The mean cube compressive strength of concrete, f_{cu}, was 48.4 MPa and approximately 80 kg of DRAMIX RL-45/50-BN steel-fibre was added per cubic metre of concrete. The aggregate maximum size was limited to 10mm for facilitating the steel-fibre distribution. The test showed that SFRC coupling beams with conventional longitudinal reinforcement depicted much higher shear capacity than regular concrete. Besides, shear capacity of specimens with a low aspect ratio was higher than those with a higher span-to-depth ratio. Furthermore, a combination of SFRC coupling beams with shear reinforcement obtained the value of shear capacities close to reinforced concrete-encased steel plates coupling beams.

Lequesne [14] also studied about the behaviour and design of High Performance Fibre Reinforced Concrete (HPFRC) coupling beams. Precast coupling beam specimens with a span-to-depth ratio of 1.75 were tested under cyclic loading. Fig. 10 describes the typical layout of HPFRC coupling beams by [14]. The experimental result presented that specimens were more ductile than RC coupling beams. Furthermore, the area of diagonal reinforcement in coupling beams can be alleviated with the usage of HPFRC. The next researcher conducted research with large-scale coupling beam specimens which consisted of slender HPFRC coupling beam specimens and a diagonally reinforced concrete coupling beam [15]. All specimens were tested under displacement reversals. The layout of the test specimens are shown in Fig. 11. The utilization of tensile strain-hardening HPFRC was intended to reduce the amount of diagonal bars and confinement. The coupling beams' aspect ratio (2.75 and 3.3), reinforcement configuration, and material type were all parameters in this research. Results from these tests showed that slender HPFRC coupling beams significantly enhanced the coupling beams' performance in terms of ductility, strength and stiffness.

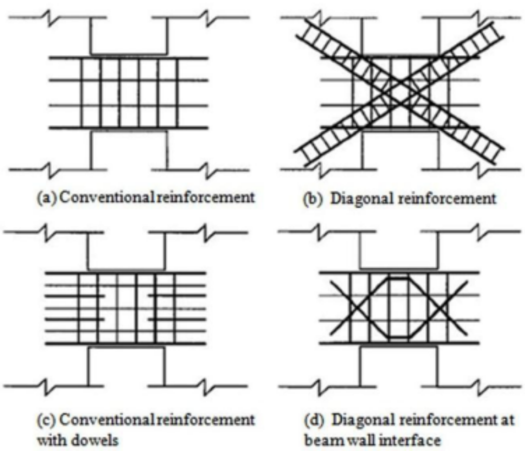

Fig.8.Specimen details of coupling beam [12].

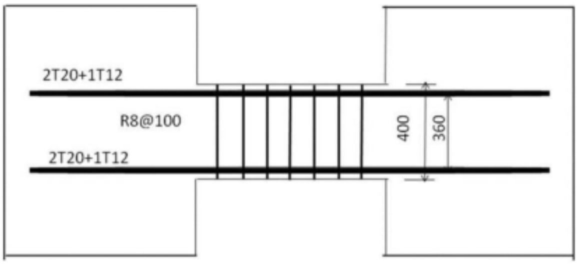

Fig.9.Dimension and reinforcement detail [13].

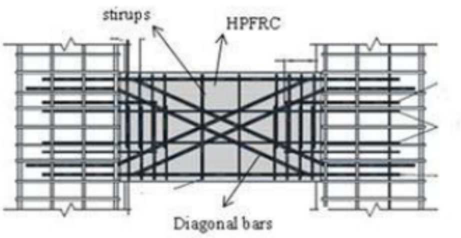

Fig.10.HPFRC coupling beams [14].

Fig.11.HPFRC coupling beams [15].

Moreover, diagonal bars could be eliminated. Setkit [15] also conducted analytical modelling using VecTor2 as a nonlinear finite element program for simulating the performance of the coupling beams. It was found that the behaviour of specimens could be predicted in VecTor2 and shear capacity that was obtained by NLFEA was in agreement with that of the experimental test.

4. Design of coupling beam according to SNI-2847-2013

In Indonesia, the guideline for the selection and detailing of reinforced concrete coupling beams for seismic design is given by SNI-2847:2013 Building Code Requirements for Structural Concrete [16], which is predominantly pertained by the sections in the provision that refers to ACI 318M-11 [17]. For beams with a span-to-depth ratio of $l_n / h \geq 4$, coupling beams are designed as flexural members that satisfy the requirements of clause 21.5 and for beams having an aspect ratio of less than 2 and a factor of shear that exceeds $0.33\lambda f_c^{'} A_{cw}$, two intersecting groups of diagonal reinforcement are required to reinforce the concrete coupling beam which is placed symmetrically diagonal in the mid-span. Each group of diagonal bars should consist of a minimum of four bars placed in a core. The required area of one group of the diagonal bar A_{vd} is (SNI 2847:2013 Clause 21.9.7.4 .a):

$$V_u = 2A_{vd} f_y \sin\alpha \le 0.83\sqrt{f_c A_{cw}} \quad (1)$$

where α is the angle between the diagonal reinforcements and the longitudinal axis of the coupling beam. Considering the importance of having sufficient anchorage for the diagonal reinforcement, it has been required that the embedment length calculated is equal to the greater of 1,25 times from the development length for f_y in tension. Furthermore, SNI 2847:2013 Clauses 21.9.7.c specifically address details for each group of diagonal bars which should be covered by transverse reinforcement which has outer dimensions to the outside is not smaller than $b_w/2$ in the direction parallel to b_w and $b_w/5$ along the other sides, where b_w is the web width of the coupling beam. The transverse reinforcement shall be parallel to the diagonal bars, not exceed six times the diameter of the diagonal bars, and shall have a spacing of hoops measured perpendicularly to the diagonal bars that does not exceed 350 mm.

The transverse reinforcement is configured as an alternative that meets the requirements of the spacing and volume ratio of transverse reinforcement along diagonals, shall continue through the intersection of the diagonal bars. Additional longitudinal and transverse reinforcement shall be distributed around the beam perimeter with a total area in each direction not less than $0.002 b_w s$ and spacing that does not exceed 300 mm. Detailing of coupling beams with diagonally oriented reinforcement is shown in Fig. 12.

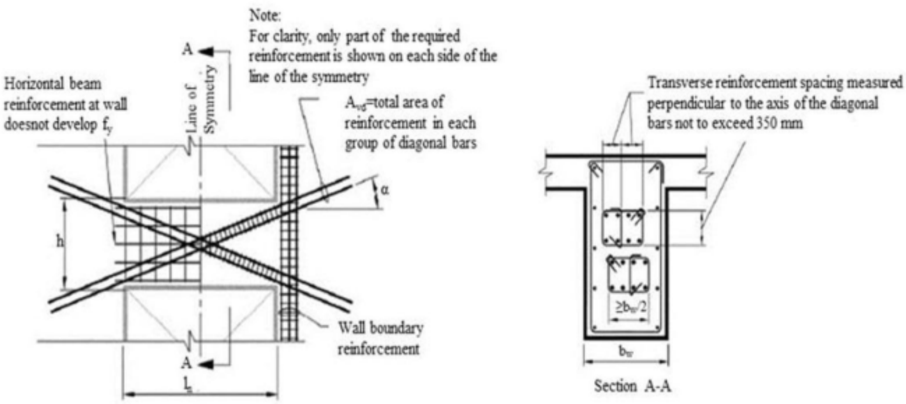

Fig.12.Confinement of individual diagonals in coupling beams [16].

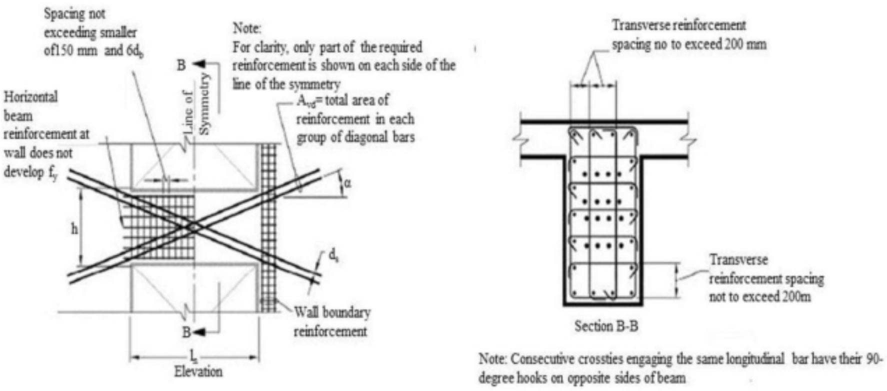

Fig. 13. Alternative confinement detailing of diagonally reinforced concrete beam section in coupling beams [16].

Another alternative reinforcement detailing for coupling beams is shown in Fig. 13. Transverse reinforcement shall be provided for the entire beam's cross-section (SNI 2847:2013 Clauses 21.9.7.d) with longitudinal spacing not smaller than 150 mm and six times the diameter of the diagonal bars, and with spacing of stirrups both vertically and horizontally in the plane of the beam cross-section that do not exceed 200 mm. Each hoop shall apply a longitudinal bar of equal or larger diameter.

Unfortunately, the utilizing of diagonal bars and reinforcement detailing required by the Indonesian Building Code [16] for maintaining seismic behaviour of structures, which is according to research by [2], is difficult to construct. The issue that arose of the use of shear reinforcement that confines the entire coupling beam instead of confining the group of diagonal bars has also been addressed in the Indonesia Building Code as a means to simplify the construction of coupling beams.

5. Further studies

Based on the experimental and numerical studies, it is shown that the result of various coupling beams provided precious and valuable information of performance in stiffness, strength and energy dissipation. However, sometimes performance of coupling beams weren't in line with simplicity of construction. Furthermore, SNI 2847:2013 as the provision of Indonesian Building Code also exhibits limited provision in the case of simplified construction of coupling beams. Because of these, there is a need to consider other feasible alternative systems of coupling beams for evaluation and to discover good performances of the whole structure. Through previous experimental investigations about shear behaviour of modified castelatted beams [18] the result was shown that the utilizing of modified castelatted beams with stiffener and composite mortar enhanced shear capacity about 340% higher than modified castelatted beams with stiffener and without composite mortar [19] and 33.33% more than castelatted beams with hexagonal opening and composite mortar [20]. In general, the utilization of mortar in modified castelatted beams with stiffener can increase the shear capacity and delay buckling. Based on these result, it is necessary to conduct further research about the feasibility of utilizing a new type of hybrid coupling beam that consists of steel truss-mortar for seismic resistance.

The proposed hybrid deep coupling beams are depicted in Fig. 14. The suggested method of hybrid deep coupling beams will be compared to the performance of diagonally reinforced concrete coupling beams based on SNI 2847:2013 Building Code Requirements for Structural Concrete. The proposed hybrid deep coupling beams comprise with the utilization of ordinary reinforced concrete beams, which resist the flexural and steel trusses that will restrain the development of high shear in coupling beams. Moreover, with the purpose of simplifying construction without ignoring the performance of coupling beams in a ductile response, the system uses steel trusses, which is easier to construct and the presence of flanges in the steel trusses may improve flexural capacity of coupling beams. This research has already begun implementation in the Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia.

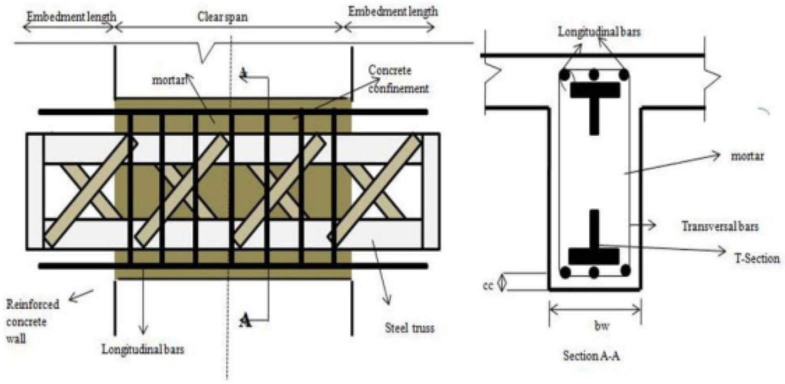

Fig.14.Proposed Hybrid Coupling Beam (Further Research)

6. Conclusion

Based on the reported study about various existing method of coupling beams and a new alternative method , the following conclusion are drawn. Although there were achievements obtained from previous studies, there were some shortages and problems that need to be solved and can be proposed as further study material. The important points are:

1. There are many reinforcement configurations for coupling beams, but with the purpose of simplifying construction, an alternative approach for the design of composite coupling beams will be needed for further studies .
2. The usage of diagonal reinforcement, the utilization of steel material, concrete as encasement, steel fiber concrete, and HPFRC materials can all enhance the seismic resistance of coupling beams. A mix and combination of these materials can be proposed for further experimental.
3. The proposed alternative coupling beams is defined as the hybrid coupling beams which is a combination between ordinary reinforced concrete beams and steel truss with composite mortar.

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