Strength performance of deep beam with embedded side plates as shear reinforcement: A numerical analysis

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Abstract. The major design criteria in deep beam is shear failure, as it is brittle in nature and causes sudden damage or collapse. Hence, research had investigated the effect of their shear strengthening method on the load carrying capacity of deep beam. This study proposed a method which replace the shear link with mild steel plate as an alternative shear reinforcement that reduce steel congestion in deep beam. Three numerical specimens were modelled using ABAQUS. The specimens were simply supported at both end and two-point loads were gradually acting on the specimens in the mode of monotonic loading condition. The results obtained from the numerical control specimen was validated with the experimental results done by other researchers. The numerical results show that the load bearing capacity of proposed deep beams were lower than the conventional specimen. The mild steel plates in proposed beams demonstrated tendency of side concrete cover separation from the main concrete body. Hence, it caused delamination of concrete leading to lower load carrying capacity.

1 Introduction

Reinforced concrete (RC) beams are designed in the form of deep beam to increase the load capacity and ensure proper load transfer in certain cases, for example corbel, transfer girder, and pile cap. According to EN1992-1-1:2004, for a RC beam which its span to depth ratio within the value of 3 will be considered as deep beam.

The major concern of engineers in deep beam is shear failure, which many literatures and researchers had been investigating shear strengthening of deep beam. Externally bonded fibre reinforced polymer (FRP) system has been commonly applied to strengthen and rehabilitating existing RC members. However, Azam & Soudki [1], and Younis et al. [2] pointed out that the bonding agent in FRP, epoxy resin not only has lower compatibility with original substrate but also release harmful gas to the working environment. Externally bonded fibre reinforced cementitious matrix (FRCM) system substitutes the epoxy resin with cementitious matrix resolves the abovementioned issues but yet facing the issue of FRCM

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debonding [1, 3-4]. Near surface embedded FRCM resolves the debonding issue [5] but this method requires specialist workmanship. Adhikary & Mutsuyoshi [6] attached continuous steel plate at the external web of RC beams. This method increases the shear capacity when the thickness and depth of steel plate increase, but the debonding of steel plate was significant as the plate thickness increase. Chen et al. [7] embedded I-shape steel section in RC deep beams found that this method causes difficulty in concrete casting as well as difficult reinforcement details at beam-to-column connection.

In view of that, the nature of deep beam requires high steel reinforcement for shear resistance. As a result, it may lead to steel congestion that can easily cause honeycomb in RC deep beam. Hence, the aim of this study is to investigate the behaviour and performance of deep beam with mild steel side plates as shear reinforcement with plates provided at various location. Previous studies on alternative shear reinforcement had encountered several problems of either susceptible to ambient environment, workmanship or special technique requirement, or steel congestion issue. Hence, the intention of this study is to replace steel shear link completely with mild steel plate in deep beam as shear reinforcement. This proposed method aims to resolve the steel congestion while preserving the shear resistance of deep beam. The feasibility of this method is studied through numerical modelling in ABAQUS finite element software and was verified by the experimental results obtained by Jasim et al. [8].

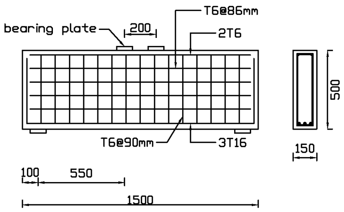
2 Methodology

Three deep beams were modelled in ABAQUS. It comprises one control specimen and two specimens where their shear links were totally replaced by mild steel plates.

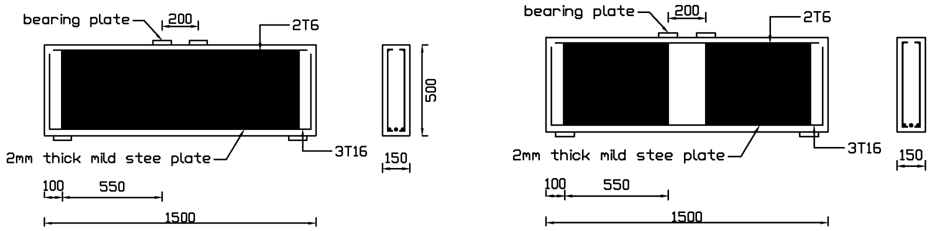
2.1 Deep beam model detailing

The constant variable was that dimension of all three specimens were 1500 mm clear span x 500 mm deep x 150 mm wide. The second constant variable was the longitudinal flexural reinforcement which the top longitudinal steel bars were 2T6 and bottom longitudinal steel bars were 3T16.

The control specimen modelled in ABAQUS was denoted as DP-S1-Num. It was verified with the experimental work carried by Jasim et al. [8] namely DP-S1-Exp. After that, two specimens with mild steel plate as shear reinforcement, DP-S2-Num and DP-S3-Num were developed and modelled using the same properties and method as in DP-S1-Num. The reinforcement detailing for DP-S1-Num, DP-S2-Num, and DP-S3-Num are illustrated in Fig. 1. In term of shear reinforcement, DP-S1-Num functioned as the control specimen, was reinforced by evenly distributed vertical and horizontal shear link. In specimen DP-S2-Num, both the vertical and horizontal shear links were replaced with 2 mm mild steel plates. In DP-S3-Num, the mild steel plates were only provided within the shear span only. The intention of excluding mild steel plate in between the centre of two loading plates was to study the overall contribution of mild steel plate towards the shear capacity within the shear span.



(a) Specimen detailing of DP-S1-Num.



(b) Specimen detailing of DP-S2-Num (c) Specimen detailing of DP-S3-Num.

Fig. 1. Specimens detailing.

2.2 Concrete modelling

The modelling approach adopted for concrete was concrete damage plasticity (CDP) model. Table 1 summarises the concrete damage plasticity parameters. The concrete beam was modelled in C3D8R elements (8-node linear bricks with reduced integration).

The concrete compression damage behaviour parameters: compressive stress (f_c), and the corresponding inelastic strain (${\epsilon_c}^{in}$) were derived based on Carreira & Chu [9]. The concrete compression damage parameter (d_c) and concrete tension damage parameter (d_t) were derived based on Lima et al. [10]. The tensile stress (σ_t) and corresponding inelastic strain (${\epsilon_t}^{in}$) were derived based on Modified Tension Stiffening Model by Wahalathantri et al. [11].

The density and Poisson's ratio of concrete was adopted as 2500 kg/m^3 and 0.2 respectively. The average 150 mm × 300 mm cylinder compressive strength of concrete based on experimental testing by Jasim et al. [8] at 28 days age, f_c' was 27 MPa. The elasticity modulus of concrete based on formulation suggested by Pauw [12] was 24,667 MPa.

Table 1. Concrete damage plasticity parameters.

Parameter	**Value**
Dilation angle	36
Eccentricity	0.1
f_{b0}/f_{c0}	1.16
K	0.667

2.3 Steel modelling

The mild steel plate and load bearing plate were modelled in C3D8R elements (8-node linear bricks with reduced integration) whereas the high yield deformed steel bar was modelled in T3D2 (2-mode linear 3-D truss). The stress-strain relation of both high yield deformed steel bar and mild steel plate were modelled in elastic-perfectly plastic model with a gentle slope derived based on Abdel-Nasser et al. [13], and the tensile and compressive behaviour are identical. Table 2 summarises the property of the steel reinforcement.

Table 2. Properties of steel.

Steel grade and type	**Density (kg/m^3)**	**Modulus of elasticity, *E* (kN/mm^2)**	**Poisson ratio, *v***	**Yield stress (N/mm^2)**
High yield steel – 6 mm diameter	7850	200,000	0.3	623.96
High yield steel – 16 mm diameter				569.67
Mild steel		70,000		367.31

2.4 Interaction properties

The interaction between concrete beam and steel reinforcement was modelled as embedded region to model the non-slip reinforcement condition. The interaction between concrete beam and mild steel plate was modelled as surface-to-surface contact with friction coefficient of 0.3 and hard contact in normal direction.

2.5 Finite element mesh sizes and loading

The element shape of concrete beam, mild steel plate, and load bearing plate were assigned as hex and were meshed with structured technique of 25 mm × 25 mm × 25 mm mesh size. The selected mesh size gives minimum impact on the accuracy of results after sensitivity study was performed. Meanwhile, the high yield steel bar was assigned as truss element with the mesh size of 25 mm. Two-point loads were gradually acting on the specimen showed in Fig. 1 in the mode of monotonic loading condition.

3 Numerical results and discussion

The numerical results and discussion were presented in terms of load-deflection curve, concrete tension damage, and stress in steel reinforcement.

3.1 Load-deflection curve

The reliability of the numerical control specimen, DP-S1-Num, was verified by comparing its load-deflection curve with the experimental control specimen, DP-S1-Exp, done by Jasim et al. [8]. Fig. 2. shows the load-deflection curve of experimental specimen and three numerical specimens. DP-S1-Exp showed that the failure load was approximately 465 kN, whereas DP-S1-Num shows slightly higher failure load of 492 kN. This result showed satisfactory agreement between the numerical and experimental results as the numerical results showed similar trend and the deviation of applied loads were within - 6.1 % to + 7.3 % for deflection between 4 mm to 6 mm. There were several factors contributing to higher capacity of this numerical specimen, DP-S1-Num. As the interaction between the concrete and steel bar was assumed to be fully bonded in numerical analysis, hence the overall stiffness of numerical specimen was found to be higher than the experimental specimen [14]. Besides that, some assumptions and variation during numerical modelling also contributes to the slight difference between experimental and numerical results such as homogeneity of concrete material, and strain softening of concrete beyond the cracking strain [8].

DP-S2-Num, which mild steel plates were used as shear reinforcement spanning from centre of support to centre of support shows a lower failure load of 414 kN compared to 465 kN for DP-S1-Exp. Attribute to the flat and smooth surface of mild steel plates, the bonding between concrete with mild steel plates was much weaker as compared to the bonding with ribbed shear link. Hence, this can easily cause the delamination of concrete at both sides which result an early failure of specimen. However, DP-S2-Num has better deflection control as part of the mild steel plate especially at the mid span act together with the bottom longitudinal steel bar, hence contributing to the flexural capacity at the early stage before the delamination of concrete.

DP-S3-Num shows the lowest failure load of 355 kN. This specimen also possesses the same delamination problem as DP-S2-Num shown in Fig. 4 (b) and (c). The factor that further reduces the failure load and deflection control was that the absent of mild steel plate at the mid span. Consequently, the overall performance of DP-S2-Num and DP-S3-Num specimens were lower than the control specimen DP-S1-Exp.

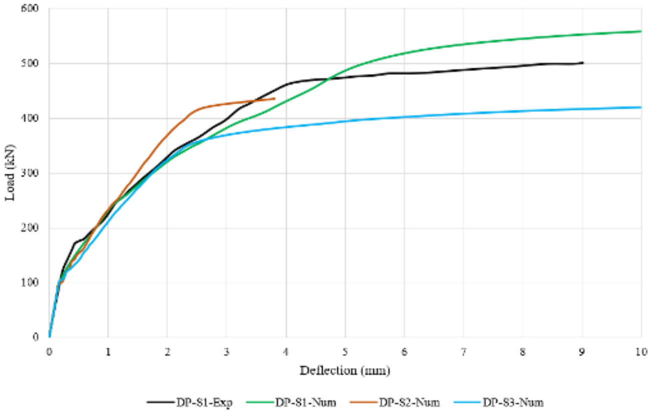
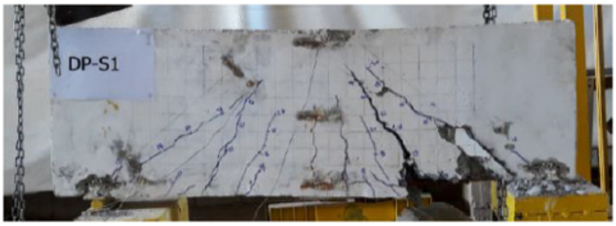


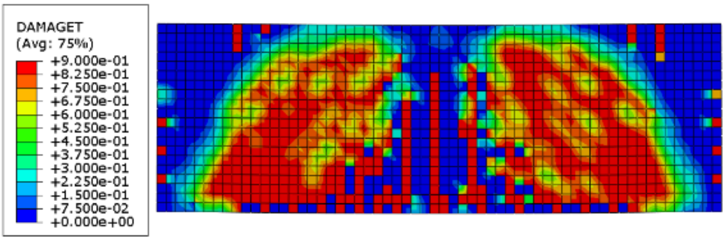
Fig. 2. Load-deflection curve.

3.2 Concrete tension damage and delamination

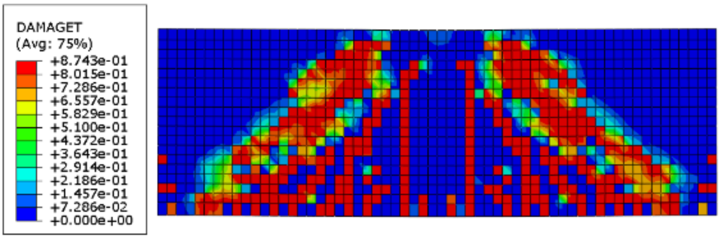
The three numerical specimens showed similar concrete crack evolution. The first crack was initiated by flexural crack at mid span, followed by flexural crack directly under the region where load applied, and then diagonal splitting at shear span. However, in specimens DP-S2-Num and DP-S3-Num, the top side of the concrete crack at the loading plate region, showing an obvious sign of concrete delamination. Fig. 3 shows the overall concrete tension damge, whereas Fig. 4 shows the concrete damage within the shear span. As discussed in Section 3.1, delamination of concrete take place when the shear reinforcment was replaced with mild steel plate in DP-S2-Num and DP-S3-Num due to the flat and smooth surface. In conventional deep beam, the vertical shear links form a close loop around the top and bottom longitudinal bars. However, in specimens DP-S2-Num and DP-S3-Num, the mild steel plates were bound to the outer side of longitudinal bars which separates the side concrete cover from the center core of concrete body. According to strut-and-tie model in deep beam, when the concrete strut in the shear span is experiencing compressive stress, it will cause tensile stress in the transverse direction. The unintentional separation created by mild steel plate will further jeopardise the delamination of concrete. Delamination of concrete were observed as a result of inconsistent tension damage across the width of the deep beam specimens as shown in Fig. 4 (b) and (c). Based on the above results, the anticipated overall cracks evolution for DP-S2-Num and DP-S3-Num's physical specimens, is shown in Fig. 5.



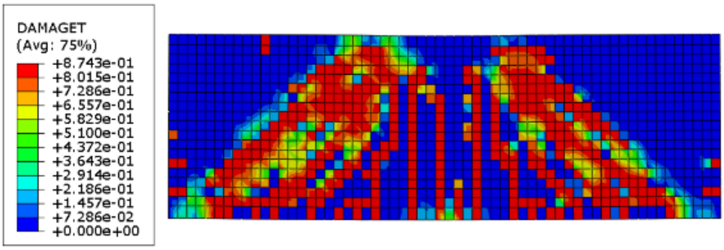
(a) Concrete cracking line of DP-S1-Exp.



(b) Concrete tension damage of DP-S1-Num at 462 kN.

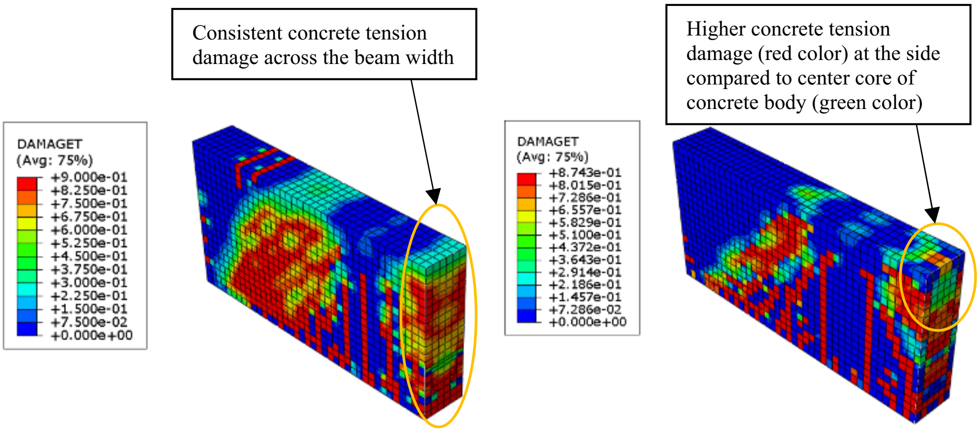


(c) Concrete tension damage of DP-S2-Num at 432 kN.



(d) Concrete tension damage of DP-S3-Num at 390 kN.

Fig. 3. Overall concrete tension damage.

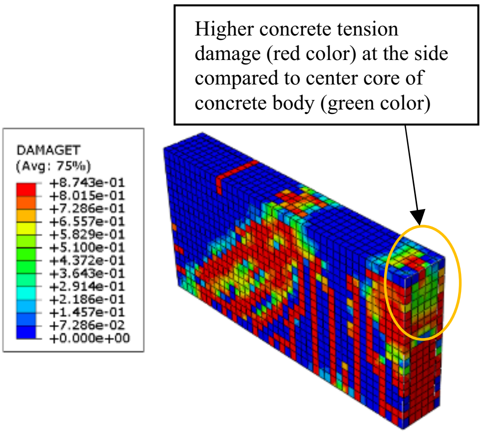


Consistent concrete tension damage across the beam width

Higher concrete tension damage (red color) at the side compared to center core of concrete body (green color)

(a) Concrete tension damage in DP-S1-Num.

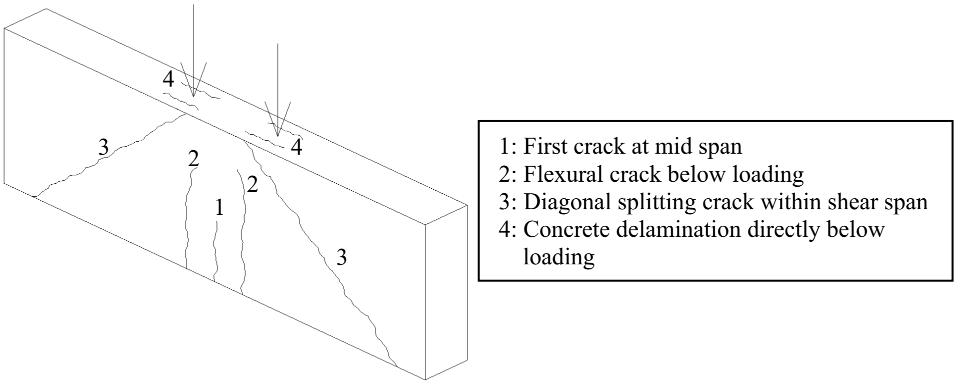
(b) Concrete delamination at shear span in DP-S2-Num.



Higher concrete tension damage (red color) at the side compared to center core of concrete body (green color)

(c) Concrete delamination at shear span in DP-S3-Num.

Fig. 4. Cross sectional cut of concrete damage within the shear span.



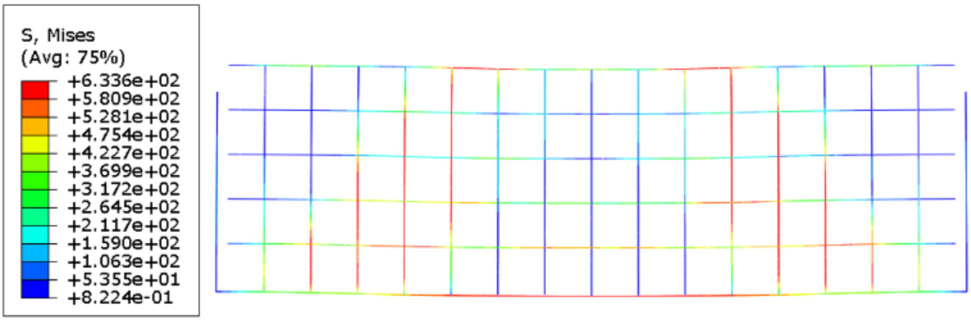
1: First crack at mid span
2: Flexural crack below loading
3: Diagonal splitting crack within shear span
4: Concrete delamination directly below loading

Fig. 5. Cracking pattern of deep beam with mild steel plate as shear reinforcement.

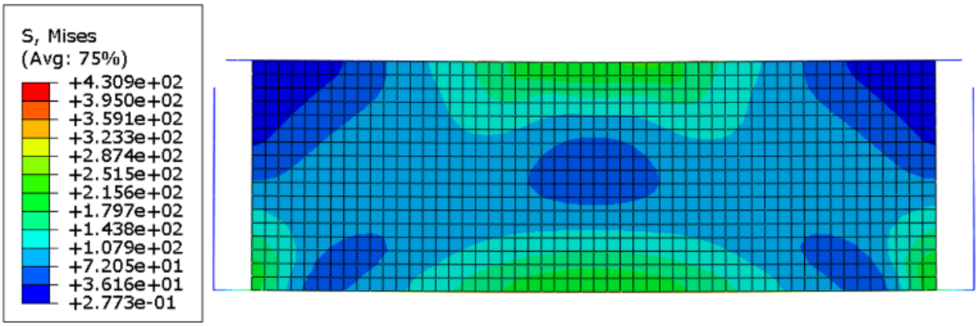
3.3 Stress in steel reinforcement

Steel reinforcement von Mises stress of DP-S1-Num in Fig. 6 (a) shows that steel within the shear span were highly stressed as compared to the bottom longitudinal steel bars. This indicates that the control specimen has higher flexural capacity than shear capacity, hence the specimen undergoes shear failure.

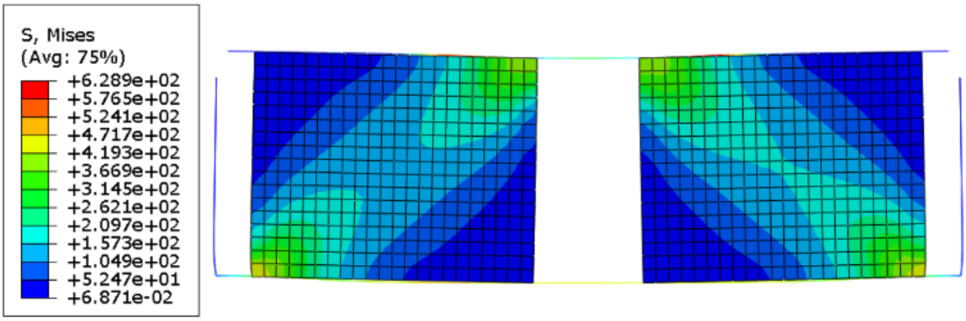
Fig. 6 (b) and (c) show that the bottom longitudinal steel bars were highly stressed as compared to steel plates within the shear span. This indicates that replacing shear reinforcement with mild steel plate in DP-S2-Num and DP-S3-Num had induced significant flexural deformation than shear deformation.



(a) Significant stress at diagonal and bottom of DP-S1-Num.



(b) Significant stress at diagonal and bottom of DP-S2-Num.



(c) Significant stress at diagonal of DP-S3-Num.

Fig. 6. von Mises stress of steel reinforcement.

4 Conclusion

In this study, a numerical study was conducted on investigating the strengths performance of deep beam with embedded side plates as new shear reinforcement. There were total of three deep beams been modelled and studied, namely one control specimen with conventional shear link as shear reinforcement (DP-S1-Num), one specimen with 2 mm mild steel plate spanning from centre of support to centre of support as shear reinforcement (DP-S2-Num), and another specimen with 2 mm mild steel plate spanning within shear span as shear reinforcement (DP-S3-Num). The numerical result of DP-S1-Num had been verified with the experimental result from Jasim et al. [8]. Thereafter, the parameters were applied to DP-S2-Num and DP-S3-Num. The results show that:

i) Replacing conventional shear link in deep beam with two thin steel plates at both sides decrease the load carrying capacity due to delamination of concrete. The two factors that lead to concrete delamination are: poor bonding between concrete and mild steel plate due to flat and smooth surface, and the detailing of mild steel plate separates the side concrete cover with the main concrete body.
ii) Replacing shear link with mild steel plate as shear reinforcement in deep beam as in DP-N2-Num, the deep beam demonstrated more flexural deformation as compared to shear deformation.
iii) By comparing with DP-S3-Num, if mild steel plate is included at the mid span as in DP-N2-Num, the bottom region of the plate shows contribution to the load carrying capacity, which eventually increase the failure load.

Based on the numerical result, in order to improve the design, it is suggested to include cut-out on the mild steel plates. The intention of this measure is to increase the bonding between mild steel plates shear reinforcement with the concrete, hence reducing the tendency of delamination of concrete that causes premature failure.

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