"Static Analysis of Multi Layers RC Deep Beams Under Combined Shear and Torsion"

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This research aims at evaluating the performance of reinforced concrete layered (hybrid) deep beams under the combined action of shear and torsion through finite element modelling using ABAQUS / CAE 2019. Concrete damage plasticity was used with meshing of a reduced integration 8-nodes linear brick element for concrete elements and a linear two-node truss element with three degrees of freedom was used for steel elements. Initially, shear and torsion models were created from experimental results of previous works on solid normal reinforced concrete deep beams. The validation of numerical results against experimental results showed mean values of 0.97, and 0.96 for at ultimate load and torque. Several hybrid deep beam were modelled from two types of concrete, fiber reinforced concrete and ultra-high strength concrete (UHSC) added in layers to normal concrete separately from 0 to 1300 mm (full thickness) with 100 mm increment each time. The simulation results indicated that the increase in the thickness of fiber reinforced concrete transferred the failure mode from single to many diagonal cracks with more detectable cracks. The mode of failure changed from combined shear and torsion to more of a torsion failure and was more pronounced for UHSC deep beams. In general, UHSC hybrid layer deep beams performed better than fiber reinforced concrete deep beams due to lower propagated damages and substantially higher ultimate loads and torques with 600 to 800 mm of each hybrid layers in the tension area provided the best behaviour. The ABAQUS software was able to accurately predict the performance of deep beams under the combined action of shear and torsion.

Keywords: Deep Beam, Shear, Torsion, ABAQUS.

1. Introduction

The aim of this study was to investigate the impact of combined shear and torsion on hybrid deep beams made from various layers of concrete material. Fiber reinforced concrete and UHSC were selected for this purpose. This paper presented the results of the study. The paper included dealt with the modelling process of deep beams including the input data of the materials and their properties. The third section provided the results of ABAQUS simulation for solid and hybrid deep beams. In addition, the results were reviewed in the final section.

This paper presented the finite element modeling approach of the study. The modeling was carried out using ABAQUS / CAE 2019. ABAQUS is a well-known engineering tool that can be used in modeling various multi physics and multi degree problems as well as predicting the performance of structural elements and materials with the assistance of user defined properties. The focus of the study is to examine the performance of deep beams under the combined action of shear and torsion. In essence, the paper will focus on the general procedure for modelling deep beams and validating the results with experimental data taken from two previous studies for the performance of the beams under shear and pure torsion. It's study included the theory and the general procedure behind the simulation of concrete and steel elements also included presented input data and modeling of deep beams of the selected studies. The validation of the developed models with the experimental data was included in the final section.

Rashid (1968) [1] developed the smeared cracking approach on which the smeared crack model is based. In this model, the detection of concrete cracking can be obtained at any location after the stresses in concrete reach a failure detention surface in a combined tension-compression or biaxial tension areas. The smeared model can model the behaviour of concrete in various structural elements such as solids, shells, trusses, and beams. The model does not detect macrocrack in the analysis. At integration points, only three cracks can occur, two of them in the plane stress and one in a uniaxial stress. As a result of damaged elasticity concepts, the calculations are impacted by the cracks. The damaged elasticity concepts can be used for describing the materials response reversible portion after the occurrence of cracking failure [2]. Even though, the smeared model is difficult to apply for 3D simulation since convergence issues are resulted from elastic stiffness damage due to plastic strains or the nonexistence of unloading or cyclic response [3]. The concrete damage plasticity model (CDP) is a continuum damage plasticity-based model proposed by Lubliner et al. (1989) [4]. The model combines the idea of isotropic damaged elasticity with compressive plasticity or isotropic tensile for presenting the inelastic concrete behaviour.

. This results in the no convergence of the modelling predictions to a solution with the refining of mesh as the refinement cause narrower crack bands rather than forming additional cracks [5]. Thus, the strain method is not recommended for modelling plain concrete. In this approach, the softening data is obtained as tabulated data for cracking strain and yield strain as shown in Fig. (1)

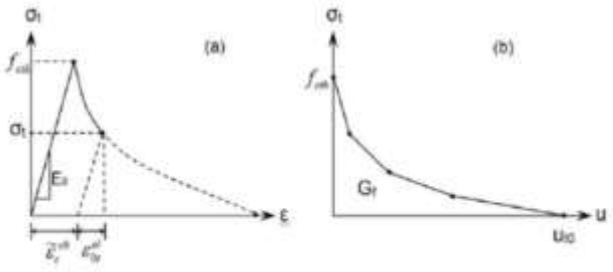
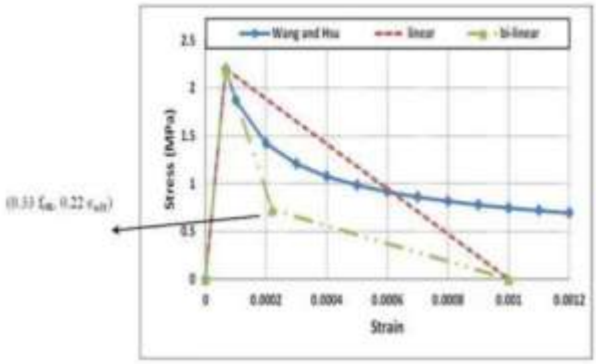


Figure .1. Post-failure tensile behaviour: (a) stress-strain approach; (b) fracture [5].

Whereas, the stress displacement and fracture energy approaches can simultaneously be used for describing the tensile behaviour of concrete since these methods are interconnected to each other cracking. These reduce the issue either the meshing dependency occurring in the strain approach and are based on the criteria of the fracture energy cracking proposed by Hillerborg et al. (1976) [6]. The methodology is based on the brittle behaviour of concrete and fracture concept and defines the fracture energy as the amount of energy required for opening a crack area as a parameter of a material. Due to the interaction between concrete and steel reinforcement, the cracked concrete initially carries some tension perpendicular to the crack. Thus, the tension stiffening effect was considered in the analysis as shown in Fig. (2). This was conducted with the assumption of gradual release of stresses of concrete normal to the plane of crack. The figure shows three curves, exponential curve known by Wang and Hsu (2001) [7], bilinear curve obtained by Peterson (1996) [8], and linear curve.

Figure .2. Uniaxial tensile stress-strain behaviour of concrete [5].

For each element in the model, the same size of mesh was assigned so that accurate results are obtained from the model. Meanwhile, the same mesh size was used for each two materials sharing the same nodes. Meshing type was chosen as structured. Three dimensional finite elements modelling was used for modelling all deep beams. For modelling the geometry, three element types are available, namely solid, shell, and wire. Concrete was modelled using solid element with the mesh type was eight nodes brick elements and hourglass control with reduced integration was used (C3D8R). This type was selected because they can be utilized in contact while the quadratic brick elements require long time for determining the nodal



loads over the surfaces. Reduced integration was selected rather than full integration. This was since full integration provides improper results because of shear locking phenomenon.

Reinforcement can be modelled using solid element thought it is computationally complicated. However, the main purpose of the reinforcement bars was to transfer normal forces and carry out tension loads. Thus, three-dimensional truss elements modelling was considered adequate since reinforcement does not provide a significant stiffness in bending. Also, for the whole analysis, assumption was made for perfect bond between concrete and steel reinforcement. Therefore, the type of truss element was three dimensional 2-node first order truss elements (T3D2 – Truss). The concrete damage plasticity modelling parameters of the developed shear and torsion models are presented in Table (1).

Table (1): Concrete damage plasticity parameters for shear or torsion

Parameter	Value
$\epsilon_{bo}/\epsilon_{co}$	1.16
ϵ	0.1
Ψ	36
μ	0 (non-viscoplastic system)
K_c	0.667

2. Research program

The first step of the research plan is to validate the proposed model using experimental data from the literature. The second segment focuses on parametric analysis.

2.1. Variation of Models

For shear model, the input of material properties was taken directly from the experimental program for solid shear specimen of Hong et al. (2002) [9] as tabulated in Table (2). In details, the beam was a rectangular shape with a cross sectional area of 600 × 150 mm. The characteristics compressive strength for concrete was obtained by a cylinder test of 300 mm length and 150 mm in diameter, equalling 23.5 mPa. A total of six longitudinal reinforcing mild steel bars were used in two layers, two at the top and four at the bottom. The diameter of the longitudinal bars was 19 mm with yield strength of 392 mPa. Mild steel stirrups were used as transverse reinforcement with a diameter 10 mm at 250 mm spacing and yield strength of 392 mPa. Details of the geometry and reinforcement of the beam is shown in Fig. (3).

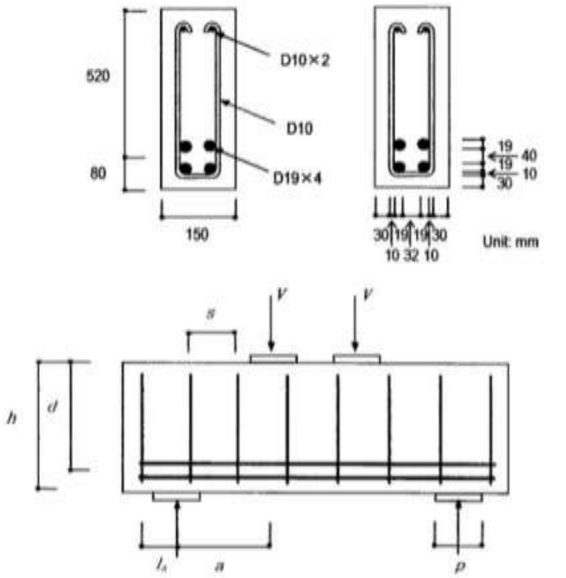


Figure .3. Details of tested deep beam under shear [9]

For continuously measuring mid-span deflection and loads, load cells and differential transformers were used. Loads were applied by an oil jack system at a rate of 9800 N/s through 150 × 150 × 5 mm steel plate and circular rollers. The developed shear model in ABAQUS is shown in Fig. (4).

Table (2): Input parameters for shear model [9]

Parameter	Value
f_c (MPa)	23.5
fy (MPa)	392
b X h (mm)	150 X 600
a (mm)	390
la (mm)	78
s (mm)	250
p (mm)	100
a/d	0.75
Concrete Density (ton/mm^3)	2.40E-09
Poisson Ratio	0.15

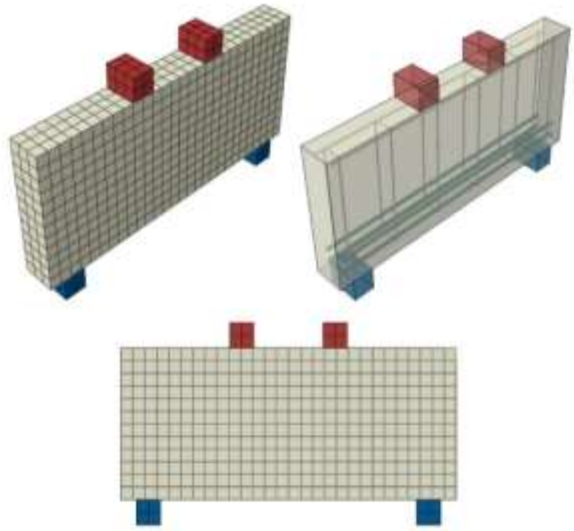


Figure (4): The developed shear model in ABAQUS.

For torsion model, the input of material properties was taken directly from the experimental program for solid torsion specimen in of Mahdi (2021) [10] as tabulated in Table (3). In details, the beam was a rectangular shape with a cross sectional area of 400 × 115 mm. The characteristics compressive strength for concrete equalled 32 mPa. A total of three longitudinal reinforcing mild steel bars were used, hooked at 90 degrees in each direction for ensuring stress development in the bars. The diameter of the longitudinal bars was 20 mm. Mild steel stirrups and shear reinforcement were used as transverse reinforcement with a diameter 8 mm at 100 mm spacing and yield strength of 392 mPa. For ensuring adequate cover thickness, spacers of 25 mm were used. Details of the geometry and reinforcement of the beam is shown in Fig. (5). The developed torsion model in ABAQUS is shown in Fig. (6).

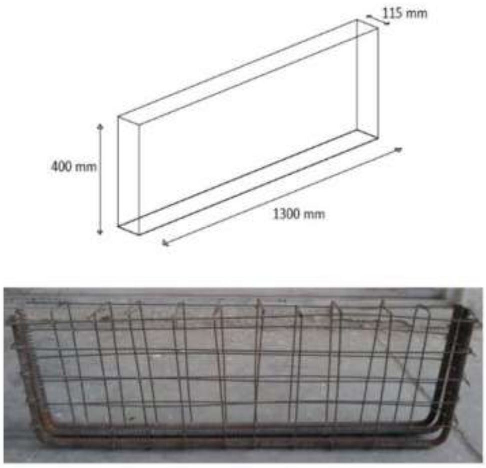


Figure (5): Details of tested deep beam under pure torsion [10].

Table (3): Input parameters for torsion model [10].

Parameter	Value
fc (MPa)	32
fy (MPa), longitudinal reinforcement	510
fy (MPa), transverse reinforcement	480
fu (MPa), longitudinal reinforcement	732
fu (MPa), transverse reinforcement	630
b X h (mm)	115 X 400
Ec	27111
Concrete Density (ton/mm^3)	2.40E-09
Poisson Ratio	0.15

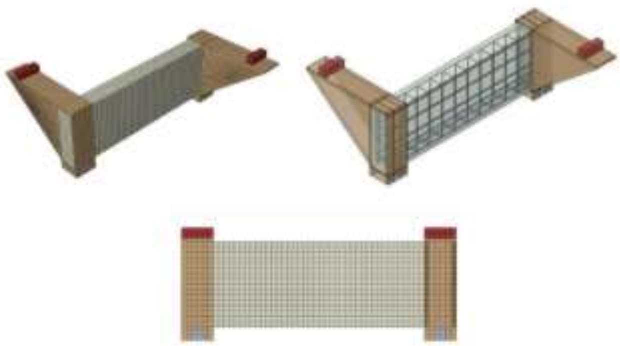


Figure (6): The developed torsion model in ABAQUS.

2.2. Parametric study

For verifying the developed models, the results of the numerical and experimental were compared. This was presented in Fig. (7) and (8) for shear and pure torsion models, respectively. Figure (7) compared the mid-span deflections that under the action of shear, which indicates a stiffer finite element results compared to experimental results. Then, after first crack the experimental results were slightly higher than the modelling results. Nevertheless, there was a good agreement between the predicted and measured maximum loads and deflections. At ultimate load, the average ratio of experimental to predicted results was 0.97 with a standard division of 0.07. This indicated that the ABAQUS software was able to accurately predict the performance of deep beams under the action of shear.

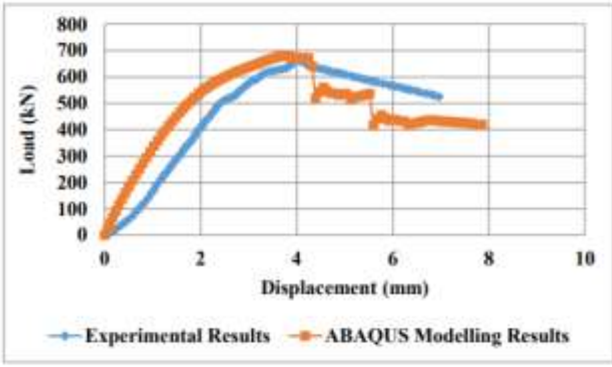


Figure (7): Comparison between experimental and ABAQUS results for deep beam under shear.

Figure (8) compared the torque and twist angles that under the action of pure torsion, which indicates a steeper finite element results compared to experimental results. Then, after some twist of the beams, the finite element data were slightly higher than the experimental results. This could be attributed to the increased stiffness of the modelling due to the development of microcracks in concrete through handling of deep beams or drying shrinkage of concrete. Finite element modelling do not include microcroacks thereby increasing the stiffness of concrete. Nevertheless, there was a good agreement between the predicted and measured maximum torques and twist angles. The mean ratio of experimental to predicted torques was 0.96 with a standard division of 0.08. This indicated that the ABAQUS software was able to accurately predict the performance of deep beams under the action of torsion.

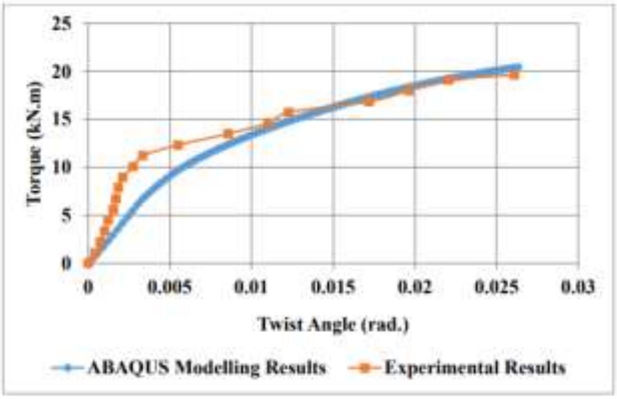


Figure (8): Comparison between experimental and ABAQUS results for deep beam under torsion.

3. Numerical analysis

3.1. Beam Testing Results and Descriptions

The dimensions of the deep beams are 3200×300×1300 mm. Two types of longitudinal main reinforcement were used; 2 of diameter 25 mm at the top and 6 of diameter 25 mm at the bottom. The stirrups were spaced at 240 mm vertically and horizontally with a diameter of 12 mm. The properties of the bars were included in Table (4). The beam model was supported at 2 support of width 200 mm each, leaving a 2800 mm clear span of the beam. The length between the centers of the supports were divided into 3 spans with the use of 2 brackets for applying the loading on the beam. The width of the bracket was 200 mm each. Thus, the length of the exterior spans between the ceter of the supports to the center of the brackets was 1000 mm each, and the length of the exterior span between the brackets was also 1000 mm. The lever arm between the center of the loading bracket and the center of beam was 500 mm. This was selected after many performed trails in order to obtain a combined shear and torsion cracking at the same time. The detailed dimensions of deep beams and reinforcement are shown in Fig. (9).

Table (4): Input data for steel reinforcement modelling.

Steel Component	Bar diameter (mm)	fu (MPa)	fy (MPa)	E (MPa)
Longitudinal	25	532.14	420.61	200,000
Stirrups	12	480	379.34	200,000

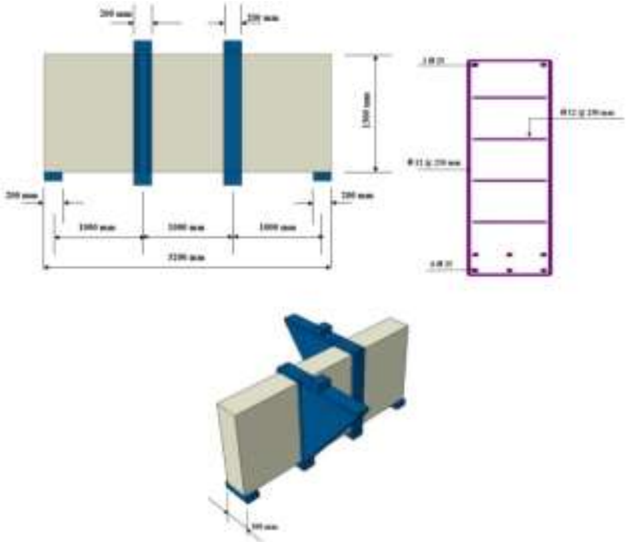


Figure (9): Detailed dimensions of deep beams and reinforcement.

4. Results and discussions

4.1. Load–deflection response

Figure (10) shows the load-deflection response of hybrid fiber reinforced and UHSC deep beams under the action of shear and torsion. The increase in the thickness of the hybrid layer shifted the initiation of cracking towards higher ultimate loading at about the same deflection. However, the crack formation area increased as well. The area of stable crack formation was not clear for solid beam and hybrid beams with thickness up to 500 mm. The increase of hybrid layer from 600 to 800 mm provided the greatest stable cracking and further increase in the thickness showed again lower and not very clear stable area of cracking. Nevertheless, the ultimate load at failure increased with the increase in the thickness of hybrid layer. The use of hybrid layer over the whole section at depth 1300 mm provided the highest ultimate load while solid beam showed the least value.

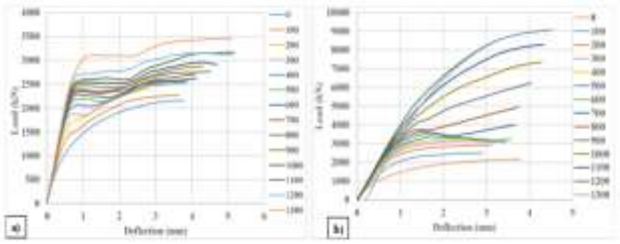


Figure (10): Load-deflection results of: a) steel fiber, and b) UHSC deep beams model in ABAQUS.

4.2. Torque-rotation results

Figure (11) shows torque versus twist angle of hybrid fiber reinforced and UHSC deep beams under the action of shear and torsion. The beams were loaded up to ultimate torque failure and the amount of corresponding twist angle was reported. The addition of hybrid layer increased the torsional strength for hybrid deep beams. The increase in the thickness of hybrid layer increased the torsional strength of concrete. Similar behaviours as revealed from the Fig. 4-37 of load-deflection curves were observed. The use of hybrid layer over the whole section at depth 1300 mm provided the torsional force while solid beam showed the least value

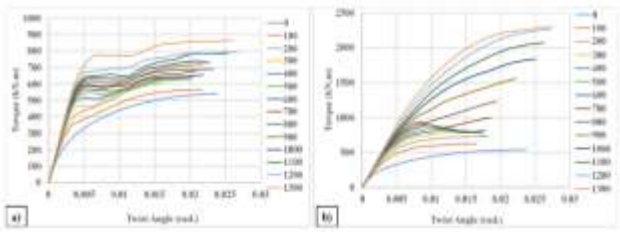


Figure (11): Torque-rotation results of: a) steel fiber, and b) UHSC deep beams model in ABAQUS.

Table (5) summaries the ultimate (Pu) loads with their corresponding displacements (Δu) per the thickness of the hybrid layer. Table (6) summaries the ultimate (Tu) torques with their corresponding twist angles (Δαu) per the thickness of the hybrid layer. The increase in Pu (ΔPu), and Tu (ΔTu) in relation to solid beam was also included as percentages in the tables. Revealing the results indicated the increase in the thickness of hybrid layer increased the ultimate loads and torques of the hybrid deep beams. The increase in the ultimate load and torques were more substantial for UHSC hybrid deep beams than fiber reinforced concrete deep beams. From simulation of ABAQUS, 600- 800 mm of fiber reinforced concrete or UHSC showed the best performance among other thicknesses of the hybrid layers. However, UHSC performed better than fiber reinforced concrete since the amount of propagated damage was lower for all thicknesses with higher ultimate loads and torques. The use of 600 mm UHSC provided ΔPu and ΔTu of 64.94% and 64.84%, respectively higher than the full fiber reinforced deep beam of 1300 mm fiber reinforcement and compared to only 21.43% and 21.34%, respectively for fiber reinforcement of the same thickness (600 mm). The use of 700 mm provided ΔPu and ΔTu of 85.44% and 85.34% for UHSC respectively, and 25.14% and 25.05% for fiber reinforcement respectively, while the use of 800 mm provided ΔPu and ΔTu of 128.85% and 128.94% for UHSC respectively, and 28.15% and 28.20% for fiber reinforcement. Since fibers reinforcement have lower axial stiffness, they transfer lower bond stresses to concrete thereby providing longer tension stiffening effect of concrete between crack and longer stiffening before the progression of cracks. The increase in the thickness of steel fiber layer provided hardening behaviour since the fibers contribute in undertaking the acted load normal to the plane of crack. The fibers bridge the cracks, providing onset of cracking without impacted on the concrete strength. At later stages of hardening response, failure took place due to the fibers pull out with the more distributed finer cracks in comparison with a single crack of softening behaviour of solid beam.

Table (5): Summary of ABAQUS simulation load-deflection results.

Hybrid Layer Thickness (mm)	Fiber reinforcement			UHSC		
	Pu (kN)	Δu (mm)	ΔPu %	Pu (kN)	Δu (mm)	ΔPu %
0	2156	3.81	0	2156	3.81	0
100	2265	3.65	5.06	2500	2.31	15.96
200	2395	2.86	11.09	2924	3.13	35.62
300	2541	3.36	17.86	3159	2.45	46.52
400	2573	3.88	19.34	3262	2.16	51.30
500	2590	3.98	20.13	3448	1.76	59.93
600	2618	4.15	21.43	3556	1.74	64.94
700	2698	4.07	25.14	3998	3.68	85.44
800	2763	4.52	28.15	4934	3.74	128.85
900	2874	4.32	33.30	6238	4.05	189.33
1000	2957	4.26	37.15	7353	4.29	241.05
1100	3143	4.35	45.78	8296	4.34	284.79
1200	3172	5.19	47.12	9067	4.45	320.55
1300	3460	5.12	60.48	9216	4.56	327.46

Table (6): Summary of ABAQUS simulation torque-rotation results.

Hybrid Layer Thickness (mm)	Fiber reinforcement			UHSC		
	Tu (kN.m)	Δαu (rad.)	ΔTu %	Tu (kN.m)	Δαu (rad.)	ΔTu %
0	539	0.024	0	539	0.024	0
100	566	0.022	5.01	625	0.017	15.96
200	599	0.016	11.13	731	0.018	35.62
300	635	0.018	17.81	790	0.014	46.57
400	643	0.02	19.29	816	0.012	51.39
500	630	0.02	16.88	846	0.01	56.96
600	654	0.022	21.34	889	0.01	64.84
700	674	0.021	25.05	999	0.019	85.34
800	691	0.023	28.20	1234	0.019	128.94
900	718	0.022	33.21	1559	0.022	189.24
1000	739	0.021	37.11	1838	0.025	241.00
1100	786	0.022	45.83	2074	0.026	284.79
1200	793	0.027	47.12	2276	0.027	322.26
1300	865	0.026	60.48	2304	0.028	327.46

5. Summary and conclusions

The research aims at investigating use of hybrid deep beams under the combined shear and torsion. Two types of concrete were studied including finer reinforced concrete and UHSC. An extensive numerical investigation was carried out using ABAQUS. A parametric study was carried out to investigate the effect of changing the thickness of the hybrid layer. Based on the numerical results, the following conclusions were drawn:

1. For validation study, acceptable agreement between experimental and numerical results were found for separate performances of deep beams under shear or torsion, through load-deflection curves, and torque-twist angle curves. At ultimate load, mean values of 0.97 and 0.96 for both curves, respectively.
2. The ABAQUS software was able to accurately predict the performance of deep beams under the combined action of shear and torsion. The software can be adopted to model the behaviour of hybrid reinforced concrete deep beams. ABAQUS is able to capture and monitor propagation and shape of cracks under loadings up to failure.
3. The impact on the behaviour of hybrid deep beam can be revealed after the onset of cracking due to produced ductile properties to the post cracking performance of the beams compared to solid deep beam. With the increase in the thickness of fiber reinforced concrete, the failure mode was transferred from single to many diagonal cracks with more detectable cracks.
4. The increase in the hybrid layer thickness resulted in propagated cracking and damages initiating and increased at the middle span changed, significantly reduced the damages at the exterior spans.
5. The ultimate load and torsional strength increased with the increase in the thickness of hybrid layer, substantially for UHSC hybrid layers. The increase in the thickness of the hybrid layer shifted the initiation of cracking towards higher loading. The use of hybrid layer

from 600 to 800 mm provided the greatest stable cracking.

6. Generally, UHSC hybrid layer deep beams performed better than fiber reinforced concrete deep beams due to lower propagated damage and higher ultimate loads and torques. For both, the use of 600 to 800 mm of hybrid layer in the tension area provided the best behaviour. The increment in ultimate loads and torques were about the same for a layer of about 21%, 25%, and 28% for 600 mm, 700 mm, and 800 mm fiber reinforcement, respectively compared to 64%, 85%, and 129% for 600 mm, 700 mm, and 800 mm UHSC, respectively.

Conflict of Interest

The authors reaffirm that there is no conflict of interest with the publishing of this article.

Abbreviations

ACI	American Concrete Institute
FEM	Finite element method
SFCR	Steel Fiber reinforced concrete
C3D8R	Continuum, 3 Dimension, 8 node, Reduced integration
T3D2	Truss, 3 Dimension, 2 node
UHSC	Ultra High Strength Concrete
RC	Reinforced Concrete

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