Shear Performance of Hybrid Concrete Deep Beams of Trapezoidal Section

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Abstract
The structural behaviour of hybrid reinforced concrete beams of trapezoidal section was investigated in this work. The main aim of study was to investigate the interaction effect of hybrid concrete compressive strength-section geometry variations on beam strength characteristics. The experimental programme included fourteen simply supported reinforced concrete deep beams being prepared and examined under a four-point load setting protocol. All specimens were of 1,000 mm length and of equal cross-sectional area. The specimens were divided into groups according to section shape variations and hybrid compressive strength considerations. Various concrete compressive strengths (70, 50, and 25) MPa were considered, and three different trapezoidal geometries of different alignment side angles (75°, 80°, and 85°) were also adopted, along with two steel rebar ratios (0.008617 and 0.01508). Generally, the experimental results showed that the shear strength capacity increased with increases in the area of high-strength concrete in the compression zone in increments, with improvements ranging from 3.66% to 8.63% as compared to reference specimens of uniform section (rectangular section); the diagonal crack load decreased, however. It was also observed that the hybrid concrete created high ductile behaviour, and the significant failure mode was shear mode without slippage of the hybrid concrete layers. A comparison of results with the hybrid strength reduction index ($\Psi=f_c'/f_a$) showed that as $\Psi$ decreased from 0.714 to 0.357, the average rating varied between 1.15 and 1.22 with respect to rectangular specimens and from 1.07 to 1.13 with respect to trapezoidal sections of uniform strength. An optimum alignment side angle for trapezoidal configuration also appears to be indicated, with the best results for all hybrid strength-trapezoidal sections in specimens where $\theta=80°$.

Keywords: Deep beam, High Strength, Hybrid concrete, Shear Strength, Trapezoidal Section.

1. Introduction
Smart distribution of section areas and optimum selection of proper strength are powerful factors in design philosophy for the creation of economic structural members. Durability, economy and reduced construction time, in addition to the factors of complexity, are the main elements affecting building success, and consideration of these elements for each part of a project ultimately leads to a decrease in the cost of build construction, as well as time savings. Among the most important parts of most construction projects are the concrete members, and thus improving their properties, increasing their strength, and using additives to allow more uncomplicated construction methods to be used contribute effectively to a project's success [1].

Among the many means of improving the properties of concrete are those that relate to increasing strength by using additives, as well as the implementation of certain forms that are appropriate to the facility in general and which contribute to an increase in durability. However, the use of hybrid concrete also contributes effectively to reducing constructions cost [2]. The concrete used in beam members must effectively utilise the compression region within the beam section, with quality and efficiency
requirements being relatively lower in tension regions. This fulfils the requirements of many global codes, the most important of which is ACI 318 [3], and makes it possible to obtain a high strength concrete beam with lower costs by using hybrid concrete and various forms of cross-section of beams. A trapezoidal shape is proportionate with the required compressive and tensile strengths, increasing the compression area and thus increasing the compression strength and vice versa for the tensile area, where rebar strength can distribute tensile stresses, thus, increasing the efficiency of such members and reducing the cost of their production. The shear strength in a reinforced concrete beam depends on concrete strength, area of effective full cross-section, stirrups, longitudinal reinforcement, and the ratio between the shear areas and depth [4]. Many researchers have studied the structural behaviour of hybrid concrete beams, and the use of composite or hybrid concrete is one of the most advanced technologies in modern construction, especially with regard to concrete beams, where researchers have benefited from knowledge of the distribution of stresses within the cross section of the beam, allowing identification of the optimal distribution of concrete within a beam so that concrete with high strength is used in the upper part of the beam while concrete with low strength can be used below. This arrangement produces concrete with high efficiency and low cost [5-14]. Other researchers have benefited from developing theory on distributing stresses within the cross section in different ways depending on the shape of the cross section, redistributing the areas inside the cross section so that the compression area is increased and the tensile area is reduced, generally resulting in a triangular or trapezoidal shape [15-18]. Others have studied the effect of non-prismatic shapes on the structural behaviour of concrete beams [19-26]. Several researchers have also studied the use of certain techniques in the production of deep beams and their effects on structural behaviour [27-36].

Most studies have dealt with just one aspect of modern technologies within the production of concrete beams, identifying the effect of a given technique on structural behaviour. In the current study, however, more than one technique has been incorporated, with hybrid concrete used with a trapezoidal cross section within a deep beam to allow the combined effect of these techniques on shear stresses to be studied.

Many other scholars and researchers have addressed the issue of shearing performance in reinforced concrete beams, and the extent of the effect of shape of cross-section and hybrid concrete on shear stresses. In 1943, Nilson [37] demonstrated the method for analysing forces in structural members as follows: as the cross-section of any structural member is exposed to external forces, those forces can be resolved into two compounds, one vertical and the other horizontal or tangential; the vertical forces cause bending moments (tensile stresses below the natural axis and compression stresses above the natural axis). The tangential component is known as the shear stresses that resist transverse shear forces. In 1973, four mechanisms were identified by the ACI-ASCE Committee [38] as transporting shear in concrete: Shear stresses are transmitted in uncracked concrete, between facades, through longitudinal reinforcement, and by arches. In 1998, the ACI-ASCE Committee 445 [39] report was issued, as a new mechanism had been identified, namely residual tensile stress transmitted directly across cracks [40]. To calculate the shear strength of a beam with a trapezoidal section with a fixed depth and length with a variation in angle, several computational methods are thus required according to the international codes that consider the beam section of special sections, which depend on determining the depth of the compression area and thus calculating the strength of concrete against various forces, including shear forces [2]. Increasing the strength of concrete contributes effectively to increasing its strength with respect to shear forces, as the beam's resistance to bending depends mainly on the strength of the upper part of the cross-sectional area. Thus, identifying the effect of using concrete with two different resistances within the same section (hybrid concrete) helps with the selection of the optimal section for shear strength at the lowest possible cost.

The use of hybrid concrete is not a new topic, and much research has addressed this topic. Several researchers have also studied the effect on the shear forces of changing the variable angle of the trapezoid, observing that the shear behaviour of the beams depends on the average cross-sectional area. Other previous studies on the effect of the use of composite concrete of two types on shear resistance have observed that shear strength, ductility, and precipitation increase when concrete with high strength
is used in the compression area. In this study, the structural behaviour of hybrid reinforced concrete beams of trapezoidal section is thus investigated with the main aim of the study being to investigate the interaction effect of hybrid concrete compressive strength and section geometry variation on beam strength characteristics.

2. Experimental methodology:

2.1 Experimental Programme

The experimental work in this study included the testing of fourteen reinforced concrete beams with lengths of 1,000 mm. Two had rectangular cross-sections, while other twelve possessed trapezoidal cross-sections with various angles as shown in Figure (1). The concrete used was of varying compressive strengths, these being 70, 50 and 25 MPa, as shown in Table (1). Four beams were cast with non-composite concrete in compressive strengths 50 and 70 MPa, while the remaining ten beams were cast using hybrid concrete (class A (fcb/fct=0.714), class B (fcb/fct=0.5), and class C (fcb/fct=0.357)); one was also cast without stirrups. Figure (2) shows the details of the reinforcement used for each beam, as shown in Plate (1).

![Figure (1). Geometrical details of specimens developed](image-url)
a- Flexural and shear reinforcement distribution

b- Cross section views of developed specimens (group 1,3)

c- Cross section views of developed specimens (group 2)

Figure (2). Steel reinforcement distribution

Plate (1). Specimen matrix
Table (1). Descriptions of tested specimens

| Group No. | Specimen symbol | Concrete compressive strength ($f_{cu}$) (MPa) | Main longitudinal steel bars reinforced | Stirrups | Cross-section width (mm) | Side* angle (degree) |
|-----------|----------------|---------------------------------------------|---------------------------------------|---------|------------------------|---------------------|
|           |                | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom | top | bottom |
| I         | BS1            | 70  | 70     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 175 | 175 | 90  |
|           | BS 2           | 70  | 70     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 250 | 100 | 75.96 |
|           | BS 3           | 70  | 50     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 250 | 100 | 75.96 |
|           | BS4            | 70  | 50     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 225 | 125 | 80.54 |
|           | BS5            | 70  | 50     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 200 | 150 | 85.24 |
| II        | BS6            | 50  | 50     | 2Ø12 | 4Ø12   | 0Ø8@50mm | 175 | 175 | 90  |
|           | BS7            | 50  | 50     | 2Ø12 | 4Ø12   | 0Ø8@50mm | 250 | 100 | 75.96 |
|           | BS8            | 50  | 25     | 2Ø12 | 4Ø12   | 0Ø8@50mm | 250 | 100 | 75.96 |
|           | BS9            | 50  | 25     | 2Ø12 | 4Ø12   | 0Ø8@50mm | 225 | 125 | 80.54 |
|           | BS10           | 50  | 25     | 2Ø12 | 4Ø12   | 0Ø8@50mm | 200 | 150 | 85.24 |
| III       | BS11           | 70  | 25     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 250 | 100 | 75.96 |
|           | BS12           | 70  | 25     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 225 | 125 | 80.54 |
|           | BS13           | 70  | 25     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 200 | 150 | 85.24 |
|           | BS14           | 70  | 25     | 2Ø12 | 7Ø12   | 0Ø8@50mm | 250 | 100 | 75.96 |

* The side angle measure is calculated with respect to the horizontal axis, as shown in Fig.(1)

2.2 Materials

The following materials were utilised across the study;

1- Cement type I was used for all concrete mixtures in this work. Iraqi cement (Karasta cement) was used (5R.42-L-A / II C), as produced by the Lafarge company and complying with ASTM and Iraqi standards specification IQS No.5/1984 [41]

2- Fine aggregate: Natural sand was used in all concrete mixtures as a fine aggregate. The maximum grain size was 4.75 mm, and the coefficient of smoothness was 2.82. Laboratory tests for sand were carried out according to Iraqi specification No. 45/1984 [42]

3- Coarse aggregate: Crushed gravel with a maximum particle size of 19mm was used as coarse aggregate for the normal strength concrete mixes. Sampling was carried out in accordance with ASTM C702-98 (reapproved 2003) [43], and the grading curve obtained lay within the ranges defined by IQR NO.45/1984.

4- Water: Reverse osmosis (R.O.) water was used in the manufacture and treatment of all concrete, as shown through laboratory testing to conform to the limits of Iraqi Standard No. 1703/1992 [44]

5- Additive: a superplasticiser (Sika ViscoCrete-225 S) was added to concrete admixtures to improve workability and compressive strength; the silica fume used in this study was an ultra-fine grey powder, commercially available under the name Mega Add MS(D), in accordance with ASTM C 1240-03[45].
6- Reinforcing Steel Bars: Ukrainian steel bars were used in the reinforced concrete beams. Steel bars with diameters of Ø12mm and Ø8mm were used as longitudinal and stirrup reinforcements and tested according to ASTM 370-0 [46].

2.3 Concrete Mixes
Several mix designs were originally considered using the British design method (BS 5328 – 2:1997) [47], and several trial mixes were created. The final mixes used are shown in Table (2), while Table (3) shows the relevant concrete properties.

| No | Compression strength | Max. aggregate. size (mm) | Cement kg/m³ | Silica Fume % | Silica Fume kg/m³ | Sand kg/m³ | Gravel kg/m³ | Superplasticizer % | Superplasticizer kg/m³ | Water/cement % |
|----|----------------------|---------------------------|-------------|--------------|------------------|------------|-------------|----------------|-------------------|--------------|
| 1  | 25                   | 19                        | 300         | 0            | 650              | 1150       | 0           | 0.5            | 2.17              | 54           |
| 2  | 50                   | 19                        | 433         | 0            | 628              | 1190       | 0.5         | 2.17           | 38                |              |
| 3  | 70                   | 19                        | 460         | 0.8          | 3.68             | 570        | 1110        | 0.06           | 2.76              | 28           |

Table 3. Concrete properties

| Batch | Compressive strength, (fcu) Mpa | Modulus of elasticity (Ec) Mpa | Splitting strength, (ft), Mpa | Rupture modulus (fr), Mpa |
|-------|---------------------------------|-------------------------------|-------------------------------|---------------------------|
| 1     | 25                              | 29962                         | 3.8                           | 3.381                     |
| 2     | 50                              | 35273                         | 3                             | 4.845                     |
| 3     | 70                              | 40134                         | 2                             | 5.612                     |

2.4 Preparation of Test Specimens
All moulds were manufactured of timber with plywood faces. These moulds were made to the required sizes to fit the standard dimensions of the beams in terms of length, depth, and upper and lower widths. All moulds were prepared, cleaned and lubricated before casting, and the reinforcing steel cages were installed within them, along with provision of the appropriate cover for the rebar, using plastic spacers. After preparation, a concrete pouring process was performed so that the concrete mixture was gradually placed in half of the mould, then the mixture was compressed using a vibrator before the second layer was cast. This was also compacted with a vibrator, after which the outer surface was levelled with a hand trowel. When the concrete hardened, the formwork was removed, and the process of water curing begun, with the concrete covered with a cloth to preserve moisture. Plate (2) shows the fabrication and casting procedure for the specimens.

Plate (2). Fabrication and casting procedure of the specimens
2.5 Test Setup

The testing process was done by supporting the beams simply from both ends, then applying a two-point centre load using a 600 KN capacity test machine. The load was increased gradually, with the rate of increase ranging from 5 to 10 kN per step until ultimate failure was reached. With each load increment, observations of deflection, strain, and crack patterns were recorded. The strain-gauges were attached perpendicular to the path between the load point and the side support and connected electrically to the data logger and personal computer, as in Plate (3).

![Plate (3). Test setting for specimens](image)

3. Results and Discussion

Table (3) displays the test results for target shear strength, ultimate load, cracking load, and deflection, in addition to the strains within the critical shear stress field paths; a brief specimen description is included in each case.

3.1 Ultimate loads and failure modes

The results show that the ultimate load increases with an increase in compression area within the cross section based on the change in alignment side angle of the trapezoidal section, while the reduction in concrete compressive strength in the tensile area only slightly affects the ultimate load. However, the predicted shear strength decrease is relatively small compared with the concrete compressive strength reduction in the tension zone, and the shear strength decrease is relatively small compared with the concrete compressive strength reduction in the tension zone. This reduces the tensile area compressive strength of concrete, while hybrid section concrete beams do not significantly affect ultimate failure load. During testing, there was no slipping between the two concrete layers of different compressive strengths, and most of the beams failed by shear, although the failure mode of beam specimen BS5 indicated flexural failure as shown in Plate (2). Table (5) shows the strength capacity of tested specimens, along with a comparison of results with the hybrid strength reduction index, which shows that as $\Psi$ decreased from 0.714 to 0.357 the average rating varied between 1.03 and 0.92 for rectangular specimens and from 0.95 to 0.85 for trapezoidal sections of uniform strength. The same finding was recorded in G2, and best result for all hybrid strength-trapezoidal sections were found in specimens where $\Theta=76^\circ$. 
### Table (4) Test results

| Group | Specimen | Description                                                                 | Ultimate Load (kN) | Deflection (mm) | Crack Load (kN) | Strain (mm/mm) |
|-------|----------|------------------------------------------------------------------------------|--------------------|----------------|----------------|----------------|
|       |          |                                                                              |                    | Ultimate       | Elastic limit  |                |
| G1    | BS1      | Rectangular (fc=70) Mpa reference (1)                                        | 510                | 5.31           | 4.3           | 146            |
|       | BS2      | Trapezoidal, 76° angle, (fc=70) Mpa, reference (2)                           | 554                | 5.73           | 4.4           | 145            |
|       | BS3      | Trapezoidal, 76° angle, (fc=70 Mpa, fcR=50 Mpa)                              | 547.6              | 6.08           | 4.6           | 150.7          |
|       | BS4      | Trapezoidal, 80° angle, (fc=70 Mpa, fcR=50 Mpa)                              | 522                | 6.2            | 5             | 141.6          |
|       | BS5      | Trapezoidal, 85° angle, (fc=70 Mpa, fcR=50 Mpa)                              | 507                | 6.11           | 4.3           | 140.5          |
| G2    | BS6      | Rectangular (fc=50) Mpa reference (3)                                        | 410                | 4.7            | 3.75          | 145            |
|       | BS7      | Trapezoidal, 76° angle, (fc=50) Mpa, reference (4)                           | 425                | 6.6            | 4.16          | 141            |
|       | BS8      | Trapezoidal, 76° angle, (fc=50 Mpa, fcR=25 Mpa)                              | 406.1              | 7.55           | 5.07          | 140.3          |
|       | BS9      | Trapezoidal, 80° angle, (fc=50 Mpa, fcR=25 Mpa)                              | 400                | 7.16           | 5.04          | 151.1          |
|       | BS10     | Trapezoidal, 85° angle, (fc=50 Mpa, fcR=25 Mpa)                              | 397                | 5.76           | 4.88          | 140.7          |
| G3    | BS11     | Trapezoidal, 85° angle, (fc=70 Mpa, fcR=25 Mpa)                              | 503                | 6.11           | 4.3           | 150.7          |
|       | BS12     | Trapezoidal, 80° angle, (fc=70 Mpa, fcR=25 Mpa)                              | 476.2              | 7.08           | 4.2           | 161.3          |
|       | BS13     | Trapezoidal, 85° angle, (fc=70 Mpa, fcR=25 Mpa)                              | 435                | 6.26           | 4.4           | 141.6          |
|       | BS14     | Trapezoidal, 76° angle, (fc=70 Mpa, fcR=25 Mpa) without stirrups             | 431                | 5.51           | 3.3           | 170.4          |
3.2 Crack Patterns
For all specimens, the first crack started near the supports, within the shear span, and developed along the specimen length. The length and size of cracks within the shear span was observed to increase in a manner directly proportional to the load increase till failure, as shown in Plate (3). The geometrical area distribution of the tension and compression zones within the cross section clearly affected the first crack load, with specimens in the second and third groups of the side angle $\theta=80^\circ$ and $\Psi=0.5$ or 0.357 recording the highest values of first crack strength, while those in the first group of the side angle $\theta=76^\circ$ and of $\Psi=0.714$ recorded the highest value for first crack load. Table (5) summarises the cracking load analysis of tested specimens. The effectiveness of using hybrid compressive strength concrete within trapezoidal sections was supported, as the hybrid strength reduction index ($\Psi$) decreased from 0.714 to 0.357 where the average rating varied between 0.99 and 1.03 with respect to rectangular specimens and from 0.99 to 1.04 with respect to trapezoidal sections of uniform strength. The same findings were recorded in specimens in G2, and best results for all hybrid strength-trapezoidal section were found in specimens of $\Theta=76^\circ$ and $\Theta=80^\circ$. The samples with $\Psi=0.357$, which had $(fc)_t=25$ MPa (G3) exhibited early cracking in comparison with those of $\Psi=0.5$ with the same $(fc)_t$ (G2); this finding confirms the effectiveness of the hybrid strength reduction index and the effects of the concrete within tension region upon cracking progression.

Plate (4). Mode failure and crack patterns
3.3 Load-deflection response

Figure (3) shows the load-deflection curves for all tested specimens; this clearly depicts specimen behaviour as being divisible into three portions. The first straight portion exhibits specimen response in the elastic range, showing identical slope and thus identical stiffness for all beams. The second region, which begins after the initiation of the first cracks, depicts the steel yielding level. This is characterised by a slight variation in the loading-deformation increment progress. The last portion represents the plastic response corresponding to strain hardening, providing steel reinforcement and showing the extent of the ultimate strength; this too was similar for all trends, though differed for corresponding load levels. The final portion of curves demonstrates lower sustainability due to the dominating failure mode of short beams which is shear or flexural-shear failure.

The results for the first and second groups showed that specimens with a trapezoidal section and with uniform concrete gave better results than specimens with a rectangular section and uniform concrete. The specimens of hybrid strength reduction index class A ($\Psi = f'_{cb}/f'_{ct} = 0.714$) and class B ($\Psi = f'_{cb}/f'_{ct} = 0.5$) both gave better results than the rectangular or trapezoidal specimens in uniform concrete. In terms of the side angle effect, the smaller angled specimens gave the highest values from.

When comparing specimens of class C ($\Psi = 0.357$), with control specimens in the first group and the second group, higher values were obtained, although the compressive strength in the tensile zone was reduced by 64.28% as compared with the first group and by 50% as compared with the second group.

The deformation response of the beam not containing stirrups (BS14), showed structural behaviour similar to the other beams. Generally, the results showed that the deflection increased with the increase in compression area, and the hybrid concrete showed a positive effect on deformation response, with values in the hybrid samples increasing as compared with those of uniform strength concrete. The specimens of class B within group (2) showed the best ductility in comparison with specimens of class A within group (1), with the latter having relatively more plastic sustainability.

Table (5) offers the mid-span deflection analysis of tested specimens, and a comparison analysis with reference specimens. The comparison of results with hybrid strength reduction index shows that as $\Psi$ decreases from 0.714 to 0.357, the average rating varies between 1.15 and 1.22 with respect to rectangular specimens, and from 1.07 to 1.13 with respect to the trapezoidal sections of uniform
strength. The same finding was recorded in G2, and the best result for all hybrid strength-trapezoidal sections was found in specimens of $\Theta=80^\circ$. 
Figure (3). Load-deflection response
| Group | Speci. | ψ  | Ultimate load (kN) | α1 | α2 | α3 | α4 | Crack load (kN) | β1 | β2 | β3 | β4 | Deflection (mm) | γ1 | γ2 | γ3 | γ4 |
|-------|-------|----|-------------------|----|----|----|----|----------------|----|----|----|----|----------------|----|----|----|----|
|       | BS1   | 1  | 510               | 1  |    |    |    |                 |    |    |    |    |                 |    |    |    |    |
|       | BS2   | 1  | 554               | 1  |    |    |    |                 |    |    |    |    |                 |    |    |    |    |
| G1    | BS3   | 0.714 | 547.6               | 1.0737 | 0.9884 |    |    |                 |    |    |    |    |                 |    |    |    |    |
|       | BS4   | 0.714 | 522               | 1.0235 | 0.9422 |    |    |                 |    |    |    |    |                 |    |    |    |    |
|       | BS5   | 0.714 | 507               | 0.9941 | 0.9151 |    |    |                 |    |    |    |    |                 |    |    |    |    |
|       | BS6   | 1  | 410               | 1  |    |    |    |                 |    |    |    |    |                 |    |    |    |    |
|       | BS7   | 1  | 425               | 1  |    |    |    |                 |    |    |    |    |                 |    |    |    |    |
| G2    | BS8   | 0.5  | 406.1              | 0.991 | 0.9555 | 140.3 |    | 0.9676 | 0.995 | 7.55 | 1.6063 | 1.1439 |
|       | BS9   | 0.5  | 400               | 0.9756 | 0.9412 | 151.1 |    | 1.0421 | 1.0716 | 7.16 | 1.5234 | 1.0848 |
|       | BS10  | 0.5  | 397               | 0.9683 | 0.9341 | 140.7 |    | 0.9703 | 0.9973 | 5.76 | 1.2255 | 0.8727 |
|       | BS11  | 0.357 | 503              | 0.9863 | 0.9079 | 150.7 | 1.0322 | 1.0393 | 6.11 | 1.1507 | 1.0663 |
|       | BS12  | 0.357 | 476.2            | 0.9337 | 0.8596 | 161.3 | 1.1048 | 1.1124 | 7.08 | 1.3333 | 1.2356 |
|       | BS13  | 0.357 | 435              | 0.8529 | 0.7852 | 141.6 | 0.9699 | 0.9766 | 6.26 | 1.1789 | 1.0925 |
|       | BS14  | 0.357 | 431              | 0.8451 | 0.778 | 170.4 | 1.1671 | 1.1752 | 5.51 | 1.0377 | 0.9616 |
3.4 Concrete strain

The measured strain of tested specimens varied according to section type and parametric considerations. All specimens within group (1) of hybrid class A exhibited strain approximately identical to rectangular and trapezoidal specimens of uniform strength (BS1, BS2). For specimens of class B within group (2), which had a hybrid ratio fć2 / fć3 = 2, the results were similar: most samples showed similar values at identical loading levels. The section area distribution of hybrid section affected normal strain response at identical loading levels significantly, however, with variation attributable to cross section side orientation angle: samples with Θ2=80° and Θ3=85° showed higher strain, Ė = 0.00338 and 0.00366, respectively, as compared to samples with Θ1=76° where Ė = 0.00223. In the third group (where concrete fć1/fć3 = 2.8), the specimen with no shear reinforcement (BS14) showed a marked decrease in strain, equal to 0.00242, while the corresponding specimen of identical dimensions in cross-section configuration with longitudinal reinforcement (BS11) showed strain equal to 0.00345.

![Figure (4). Load-strain responses](image-url)
3.5 Trapezoidal section area distribution effectiveness

Figure (5) clearly denotes the effectiveness of the trapezoidal section area with regard to distribution of ultimate shear strength. The geometry for all tested beams of various hybrid sections indicates a reduction in strength. The compression zone area and enhanced ultimate shear strength increased when the section compression zone extension (Θ) changed from 85 to 76. This observation confirms the compatibility of the trapezoidal section with the development of efficient compression stress blocks with proper tension zones, and no significant effects of hybrid strength reduction upon tension zone performance was observed with respect to the predicted failure modes.

4. Conclusion

1- The hybrid-trapezoidal sections of reinforced concrete beams recorded values close to the ultimate shear strength and an improvement in ductility response where the mid span deflection ranged from 6.11% to 7.91% as compared with control specimens, in spite of the hybrid-trapezoidal section demonstrating a significant reduction in concrete compressive strength within the tensile region across the specimen section, with hybrid strength ratings varying from 0.357 to 0.714.
2- The geometrical area distribution of the tension and compression zones within the cross section clearly affect the first crack load, with specimens in the second and third groups of side angle $\theta=80$ and $\Psi=0.5$ or 0.357 recording the highest values of first crack strength, while the first group of side angle $\theta=76$ and $\Psi=0.714$ recorded the highest value for first crack load.

3- The influence of hybrid strength rating upon ductility index was confirmed, with specimens of class B (moderated hybrid strength rating $\Psi=0.5$) within group 2 exhibiting the best ductility responses within group (1), where the last portion of the load-deformation curve has relatively more plastic sustainability for specimens of hybrid class B.

4- The results show that the first crack load decreases with a decrease in concrete strength under flexural tensile stresses within the cross section, while increasing with an increasing in concrete compressive strength from concrete volume under flexural compressive stresses within the cross section.

5- The section area distribution of hybrid sections affects normal strain responses at identical loading levels significantly; this variance is sensitive to cross section side orientation angle, with samples from $\Theta_2=80^\circ$ and $\Theta_3=85^\circ$ showing higher strain at $\epsilon=0.00338$ and 0.00366, respectively, as compared to $\Theta_1=76^\circ$, where $\epsilon=0.00223$.

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Notation

- $f_{cb}$ Concrete compressive strength at bottom beam section, MPa
- $f_{ct}$ Concrete compressive strength at top beam section, MPa.
- $f'_{cu}$ Concrete compressive strength, MPa
- $E_c$ Modulus of elasticity, MPa
- $f_s$ Splitting strength, MPa
- $f_r$ Rupture modulus, MPa
- $\Psi$ Hybrid strength reduction index ($\Psi = f_{cb}/f'_{cu}$)
- $\alpha_i$ Ultimate load rating with respect to reference specimen i
- $\beta_i$ Crack load rating with respect to reference specimen i
- $\gamma_i$ Deflection rating with respect to reference specimen i