



Shear Response of Reinforced Concrete Beams Containing Recycled Coarse Aggregate under 45° Biaxial Loading: Experimental Testing and Finite Element Analysis

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ABSTRACT

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recycled aggregate concrete, reinforced concrete beams, biaxial shear loading, diagonal cracking, ultimate load, Concrete Damaged Plasticity, finite element analysis

This study examines the shear response of reinforced concrete beams containing recycled coarse aggregate (RCA) under 45° biaxial loading through laboratory testing and three-dimensional finite element analysis. Eight beams with square and rectangular cross-sections were cast and tested, with natural coarse aggregate replaced by RCA at 0%, 30%, 50%, and 75%. The inclined loading arrangement was selected to create a combined shear action and trigger diagonal cracking, thereby allowing the influence of RCA content and section geometry on shear-dominated failure to be assessed. A nonlinear finite element model was developed in ABAQUS using the Concrete Damaged Plasticity (CDP) model, with material parameters defined from experimentally derived stress-strain relationships. The model was evaluated against the test results using cracking load, ultimate load, failure mode, and observed crack patterns. The experimental results show that higher RCA replacement generally lowered both cracking and ultimate loads and produced wider, more evident diagonal shear cracks, with the most marked reduction observed at 75% replacement. The finite element predictions were consistent with the measured load response and reproduced the main features of the observed shear failure. Within the limits of the beam sizes, aggregate source, replacement ratios, and loading setup examined here, RCA replacement of up to 50% can provide acceptable structural performance for beams subjected to this biaxial shear condition.

1. INTRODUCTION

Shear failure in reinforced concrete beams is a brittle mode of failure that occurs with little or no prior warning, making it one of the most critical limit states in structural design [1]. In practical reinforced concrete structures, beams may experience shear forces acting simultaneously in two orthogonal directions due to three-dimensional load transfer in spatial frames, bridge decks, and edge beams. Such multidirectional shear actions alter crack formation, principal stress orientation, and shear resistance compared to conventional uniaxial shear conditions. Therefore, understanding the behavior of reinforced concrete members under biaxial shear loading is essential for reliable evaluation of structural safety and load-carrying capacity [2-4].

The orientation of biaxial shear loading relative to the beam cross-section significantly influences crack propagation, shear transfer mechanisms, and energy dissipation capacity of reinforced concrete elements [5, 6]. In the present study, a 45° loading configuration was adopted because it generates a combined shear stress state and promotes the formation of diagonal shear cracks, representing a critical condition for investigating biaxial shear behavior in reinforced concrete

beams. Although most previous studies on biaxial shear behavior have focused on columns and walls, reinforced concrete beams subjected to bidirectional shear loading have received comparatively limited experimental attention, despite their practical presence in edge beams, transfer girders, and bridge systems [4, 7].

In addition to loading complexity, material sustainability has recently become an important consideration in structural concrete applications. The incorporation of recycled coarse aggregate (RCA) in reinforced concrete beams affects shear strength, crack development, and energy absorption capacity due to variations in the interfacial transition zone (ITZ) and aggregate stiffness compared with natural-aggregate concrete [8, 9]. Most existing experimental studies on reinforced concrete beams containing RCA have been conducted under uniaxial loading conditions and have mainly focused on flexural or shear behavior separately rather than under multidirectional shear actions [10, 11].

Despite the increasing number of studies on recycled aggregate concrete beams and the growing interest in biaxial shear behavior of reinforced concrete members, experimental data on reinforced concrete beams incorporating RCA and subjected to 45° biaxial shear loading without torsional effects

remain limited [5, 11]. Furthermore, the influence of cross-sectional geometry on the shear response of RCA beams under such loading conditions has not been sufficiently investigated.

This study presents an experimental and numerical investigation of reinforced concrete beams incorporating RCA subjected to a 45° biaxial shear loading configuration without torsion. Square and rectangular beam sections were tested to evaluate the influence of cross-sectional geometry and RCA replacement ratio on shear behavior. In addition, nonlinear finite element modeling using ABAQUS was performed to simulate the structural response, crack development, and failure mechanisms observed experimentally.

2. EXPERIMENTAL PROGRAM

2.1 Geometry and materials

Eight reinforced concrete beam specimens were fabricated and tested to evaluate the combined influence of cross-sectional geometry and RCA content on biaxial shear behavior. The beams were divided into two groups according to cross-sectional shape: square and rectangular, with four specimens in each group. The square beams had cross-sectional dimensions of 250 × 250 mm, whereas the rectangular beams measured 150 × 350 mm, as shown in Figure 1.

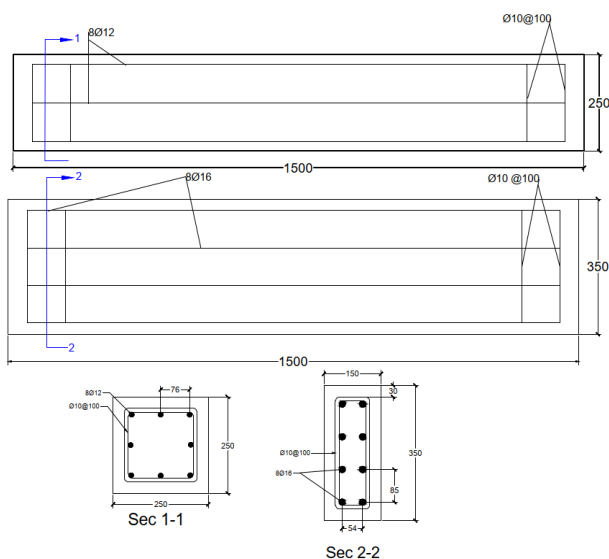


Figure 1. Longitudinal and transverse reinforcement details of the tested reinforced concrete (RC) beams with cross-sections 1-1 and 2-2

All beams were cast with a total length of 1500 mm and tested under simply supported conditions over a clear span of 1300 mm, with a support width of 100 mm at each end. Steel bearing plates were placed at the supports and at the loading point to ensure uniform load transfer and to prevent local crushing of concrete. The load was applied at midspan along a 45° orientation relative to the principal section axes to induce biaxial shear action. The adopted span-to-depth ratios and boundary conditions were selected to promote shear-dominated behavior representative of short reinforced concrete beams subjected to combined shear actions [1].

Four concrete mixtures were prepared by partially replacing

natural coarse aggregate with RCA at replacement levels of 0%, 30%, 50%, and 75% by mass. Ordinary Portland Cement complying with the Iraqi Specification No. 5/1984 and ASTM C150 requirements was used throughout the experimental program. All concrete mixtures were prepared with a constant water-to-cement ratio (w/c) of 0.43. Natural river sand was used as fine aggregate, while conventional river gravel was used as natural coarse aggregate. The RCA was obtained by crushing previously tested concrete specimens collected from the structural laboratory. Before mixing, the recycled aggregate was cleaned, sieved, and used in an air-dried condition. Both natural and RCAs had a nominal maximum size of 20 mm, and the aggregate grading complied with the standard limits, as illustrated in Figure 2.

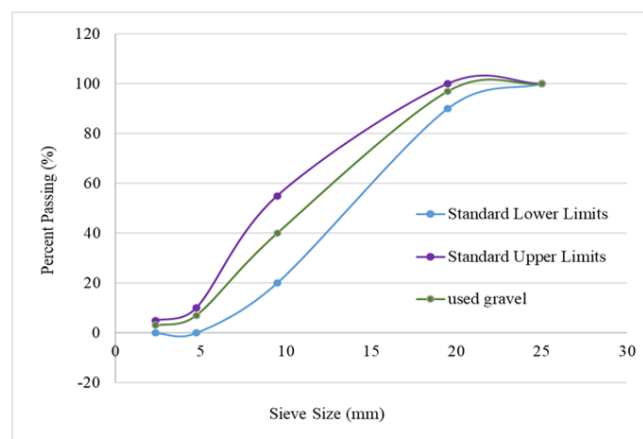


Figure 2. Grading curve of the used coarse aggregate compared with the standard upper and lower grading limits

A high-range water-reducing admixture (Sika® ViscoCrete®-905) conforming to ASTM C494 was used to improve concrete workability, particularly for mixtures containing RCA. All beam specimens were cast and cured under similar laboratory conditions. After casting, the specimens were demolded after 24 hours and cured in water until the testing age of 28 days.

Compressive strength was determined at 28 days using six 150 mm cube specimens for each mixture. The resulting average compressive strengths corresponding to each replacement ratio are reported in Table 1. For each RCA level, one square beam and one rectangular beam were cast to investigate the influence of cross-sectional geometry and RCA replacement ratio on the structural response of the tested beams.

Table 1. Mechanical properties of concrete mixtures with different recycled coarse aggregate (RCA) replacement ratios at 28 days

Mix ID	RCA Replacement (%)	Compressive Strength f_{cu} (MPa)	Split Tensile Strength (MPa)
RCA-0	0	40	3.47
RCA-30	30	33.4	2.77
RCA-50	50	31	1.94
RCA-75	75	23	1.39

All specimens were reinforced with eight longitudinal deformed bars distributed along the perimeter of the beam cross-section and enclosed by a nominal concrete cover of 25

mm, as illustrated in Figure 1. Bar diameters of 12 mm and 16 mm were used in the square and rectangular beams, respectively, in accordance with the dimensions and structural configuration of each beam group. No transverse reinforcement was provided within the shear span to avoid additional shear contribution from stirrups and to ensure that failure was governed by concrete shear resistance [2]. To maintain the position of longitudinal reinforcement during casting, two closed 10 mm stirrups were placed only near each support region. This detailing ensured that all beams remained shear-critical and failed within the span under biaxial shear loading.

2.2 Test setup, measurement devices, and loading conditions

The reinforced concrete beam specimens were tested under simply supported conditions to investigate their structural response under biaxial shear loading. To produce the required loading inclination, each beam was rotated about its longitudinal axis so that the applied load acted at an angle of 45° relative to the vertical axis.

Inclined steel supports were installed at both ends to maintain the specified orientation during testing. A steel load-transfer block was positioned at midspan to ensure that the applied load was aligned with the inclination of the supports and passed through the shear center of the beam section in Figure 3.

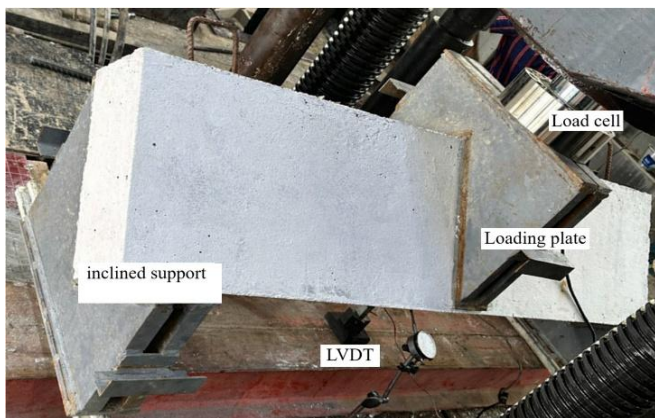


Figure 3. Experimental setup showing the inclined support, loading plate, load cell, and linear variable differential transformer (LVDT) used during the biaxial loading test

All specimens were tested after 28 days of curing. Before testing, the beam surfaces were cleaned and painted to facilitate clear observation of crack initiation and propagation. Loading was applied monotonically under load-control mode in increments of 5 kN until failure occurred.

The applied load was measured using a calibrated load cell, and the readings were recorded through a data acquisition system. Vertical deflection at the bottom of midspan was monitored using a linear variable differential transformer (LVDT) to capture the overall load–deflection response. Shear deformation within the shear span was measured using mechanical strain gauges (Demec points) with a gauge length of 50 mm. Three pairs of Demec points were installed at a 45° orientation within the shear span to represent the principal shear directions. Electrical strain gauges were attached to the longitudinal reinforcement to measure strains in the extreme tension and compression bars during loading.

During testing, the loads corresponding to first-crack load (P_{cr}) and ultimate load (P_u) were recorded. Crack initiation and propagation were continuously monitored, and the failure mode of each specimen was carefully documented.

For clarity, a simplified specimen designation system was adopted. The label “RE” refers to rectangular beams, and “SQ” denotes square beams, followed by the RCA replacement ratio. Accordingly, the specimens were designated as RE-0, RE-30, RE-50, RE-75, and SQ-0, SQ-30, SQ-50, SQ-75.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Failure modes and crack patterns

The failure modes and crack patterns of the tested beams subjected to a 45° loading angle are presented in Figure 4 for the rectangular and square beams. In all specimens, failure was governed by the formation of a dominant diagonal shear crack extending between the support region and the loading zone, which is characteristic of shear-controlled behavior in beams without transverse reinforcement.

At the early stages of loading, fine flexural cracks appeared near the midspan of the beams within the tension zone. As the load increased, these cracks remained relatively limited while a major diagonal shear crack suddenly developed shortly before failure. This crack rapidly propagated through the beam depth toward the compression zone, leading to a sudden reduction in the load-carrying capacity.

For the control specimens produced with natural aggregate (RE-0 and SQ-0), the failure was characterized by a single dominant diagonal crack accompanied by limited secondary cracking. With increasing RCA content, the diagonal cracking became more pronounced and extended over a larger portion of the beam depth. In specimens containing higher RCA ratios, particularly 50% and 75%, the cracks appeared wider and more irregular, indicating a more brittle failure response.



(a)



(b)



(c)

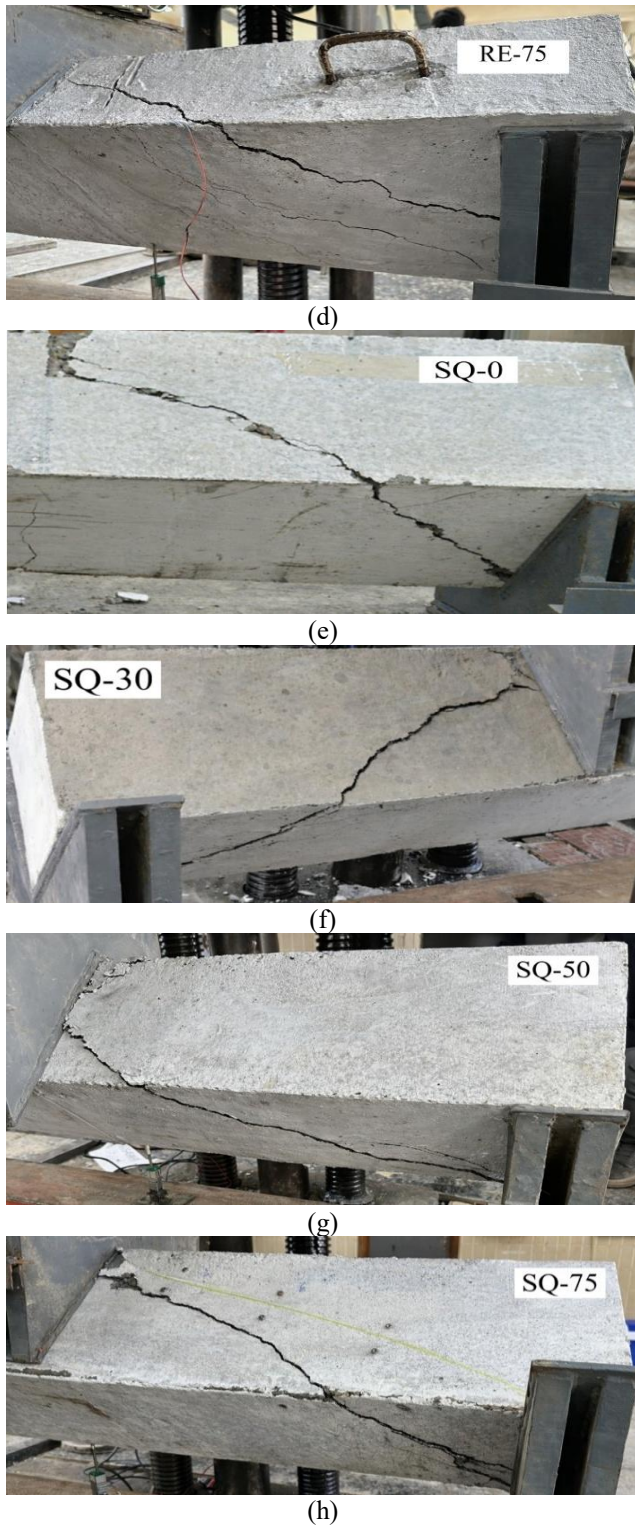


Figure 4. Cracking patterns and failure modes of reinforced concrete beams without shear reinforcement tested under 45° biaxial loading: (a) RE-0, (b) RE-30, (c) RE-50, and (d) RE-75, (e) SQ-0, (f) SQ-30, (g) SQ-50, and (h) SQ-75
Note: RE: rectangular beams; SQ: square beams.

These observations may be associated with the reduced stiffness and weaker ITZ commonly reported for recycled aggregate concrete, which can accelerate crack initiation and propagation under shear-dominated stress conditions. Consequently, the ability of the concrete matrix to redistribute stresses within the shear span decreases as the RCA replacement ratio increases. Similar trends have been reported in previous studies on recycled aggregate concrete beams

subjected to shear loading [12-14].

Overall, the experimental observations indicate that although the cross-sectional geometry slightly affects the crack distribution, the governing failure mechanism remains similar for both square and rectangular beams under biaxial loading. The increase in RCA content primarily influences the crack development, crack continuity, and brittleness of failure rather than the fundamental failure mode.

The observed failure patterns can be interpreted in terms of the internal stress redistribution within the shear span under inclined loading. When the load is applied at an angle of 45°, the principal stress trajectories rotate, and a diagonal compression field develops between the support and the loading point. This stress field leads to the formation of a dominant diagonal crack, after which the shear resistance is mainly governed by the concrete compression strut and aggregate interlock along the crack surface.

In beams without transverse reinforcement, the stability of this compression strut becomes the controlling factor for the ultimate shear capacity. The presence of RCA may influence this mechanism through changes in the concrete microstructure and the ITZ between the aggregate particles and the cement matrix [15, 16]. As a result, the aggregate interlock capacity and crack-bridging resistance are reduced, which may contribute to faster crack propagation and a more brittle failure response at higher RCA replacement ratios.

These observations are consistent with the shear transfer mechanisms described in the modified compression field theory and in experimental investigations on recycled aggregate concrete beams subjected to shear-dominated loading [17-19].

Table 2. First-crack load (P_{cr}) and ultimate load (P_u) of tested beams

Beam Identification	P_{cr} (kN)	P_u (kN)	P_{cr}/P_u (%)
SQ-0	40	136.8	29%
SQ-30	34.34	158.8	22%
SQ-50	25	137.65	18.2%
SQ-75	20	105.75	19%
RE-0	35	149	23.5%
RE-30	34.34	126	27.2%
RE-50	20	108	18.5%
RE-75	20	99.25	20.2%

Note: RE: rectangular beams; SQ: square beams.

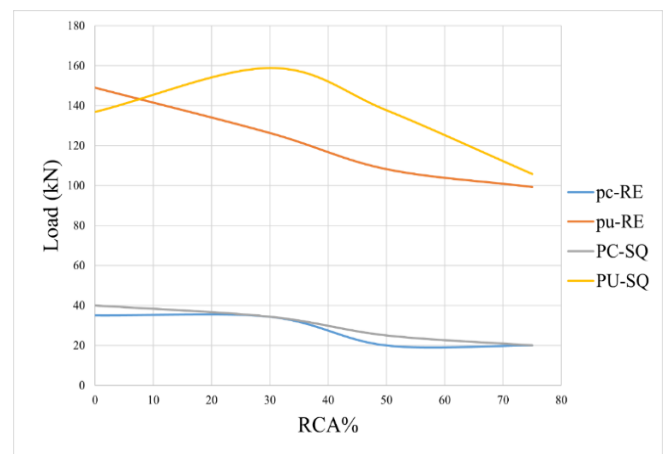


Figure 5. Variation of the first-crack load (P_{cr}) and ultimate load (P_u) with recycled coarse aggregate (RCA) replacement ratio for rectangular and square beams
Note: RE: rectangular beams; SQ: square beams.

3.2 Ultimate load and first-crack load

Table 2 summarizes the values of the P_{cr} and P_u for all tested beams with different RCA replacement ratios. The variation of these loads with RCA content is illustrated in Figure 5 for the square and rectangular beams.

The P_u did not exhibit a strictly decreasing trend with increasing RCA content. However, a slight increase in P_u was experimentally observed at a moderate replacement ratio of approximately 30%, which is generally consistent with observations reported in previous studies on recycled aggregate concrete beams [8, 18, 20]. When the RCA content increased to 50% and 75%, a more noticeable reduction in the P_u was recorded, which may be associated with changes in the concrete microstructure and weaker bond characteristics between recycled aggregates and the cement matrix [16, 21].

In addition, the P_{cr}/P_u ratio generally decreased with increasing RCA content, indicating that cracking occurred earlier relative to the ultimate failure. This behavior suggests that beams containing higher proportions of recycled aggregates may exhibit earlier crack development and a more pronounced shear-dominated response after crack initiation.

Overall, although the cross-sectional geometry influenced the absolute values of P_{cr} and P_u , the general behavior remained consistent for both square and rectangular beams. Increasing the RCA replacement ratio was generally associated with earlier crack initiation and a gradual reduction in P_u capacity, particularly at higher replacement levels.

P_{cr} generally decreased with increasing RCA replacement ratio. This reduction suggests that recycled aggregate concrete may exhibit lower tensile resistance compared with conventional concrete, possibly due to the higher porosity of recycled aggregates and the weaker ITZ between the aggregate particles and the cement paste. Similar reductions in cracking resistance have been reported in previous experimental studies on recycled aggregate concrete beams [17, 19].

3.3 Midspan deflection

The load–midspan deflection curves obtained from the experimental tests are presented in Figure 6 and Figure 7 for the square and rectangular beams, respectively. These curves describe the structural response of the beams from the initial elastic stage until failure. In general, all tested beams exhibited a similar behavioral pattern consisting of an initial linear elastic stage, followed by a cracking stage characterized by stiffness degradation, and finally a nonlinear stage leading to ultimate failure.

At the early stage of loading, the load–deflection relationship was approximately linear, indicating that the beams remained within the elastic range before the formation of visible cracks. As the load increased and the first flexural cracks appeared in the tension zone, the stiffness of the beams gradually decreased due to crack propagation within the shear span. Consequently, the curves deviated from linearity and entered the nonlinear stage where the deflection increased more rapidly until the P_u was reached.

The influence of the RCA replacement ratio is clearly observed in the load–deflection response of the beams. As the RCA content increased from 0% to 75%, the stiffness of the beams decreased, leading to larger midspan deflections under the same load level. In addition, the reduction in stiffness becomes more pronounced at higher RCA replacement levels (50% and 75%), where the load–deflection curves show a

flatter slope after cracking and a more noticeable reduction in P_u capacity. This behavior may be associated with the presence of adhered old mortar on recycled aggregates, which can result in multiple and weaker ITZs within the concrete matrix. These weaker zones may facilitate crack initiation and propagation, thereby reducing the overall stiffness of the beams [21–23].

Despite this reduction, the general shape of the curves remained broadly similar for all specimens, indicating that the fundamental load-transfer mechanism of the reinforced concrete beams is preserved even when natural aggregates are partially replaced with recycled aggregates. Furthermore, the influence of cross-section geometry can also be observed when comparing the square and rectangular beams. The rectangular specimens generally exhibited slightly higher stiffness and greater P_u capacity than the square beams. This behavior can be attributed to the difference in cross-section geometry, where the rectangular beams possess a larger moment of inertia in the loading direction, which enhances their flexural stiffness and delays the development of excessive midspan deflection.

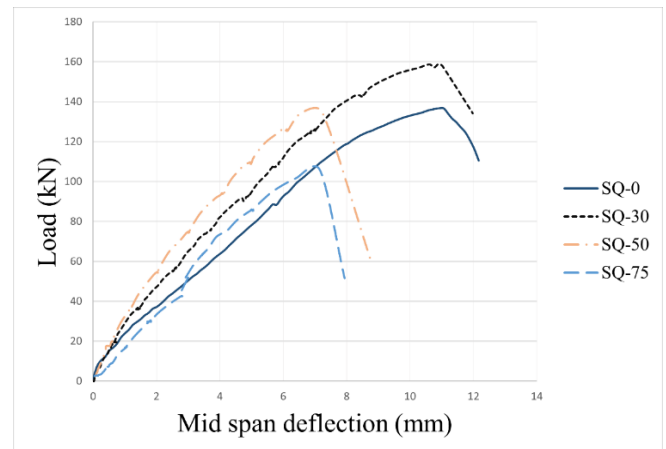


Figure 6. Load–midspan deflection curves of square beams with different recycled coarse aggregate (RCA) replacement ratios
Note: SQ: square beams.

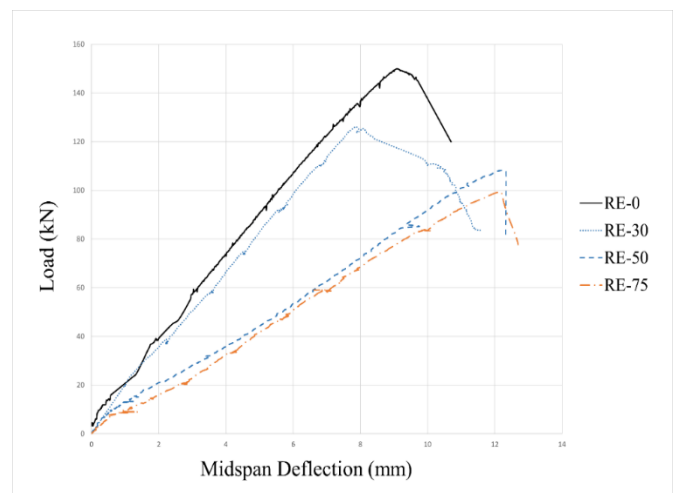


Figure 7. Load–midspan deflection curves of rectangular beams with different recycled coarse aggregate (RCA) replacement ratios
Note: RE: rectangular beams.

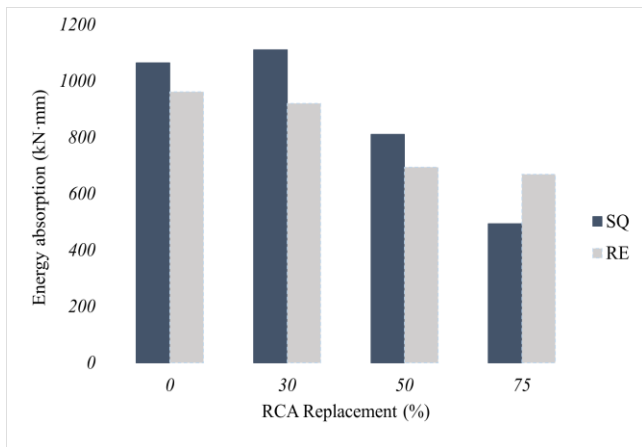


Figure 8. Energy absorption capacity of square and rectangular beams with different recycled coarse aggregate (RCA) replacement ratios
Note: RE: rectangular beams; SQ: square beams.

Due to the shear-dominated failure observed in the tested beams, yielding of the longitudinal reinforcement was not clearly reached before failure. Therefore, a conventional displacement ductility index was not evaluated. Nevertheless, the load–deflection curves indicate limited deformation capacity, which is typical for shear-critical reinforced concrete members.

3.4 Energy absorption capacity

Figure 8 presents the variation of energy absorption capacity for square and rectangular beams with different RCA replacement ratios. The energy absorption was evaluated as the area under the load–deflection curve up to failure, which represents the ability of the beam to dissipate energy through deformation [5, 24].

For the square beams, the energy absorption initially increased with the introduction of recycled aggregates and reached its maximum at a moderate replacement level. This behavior suggests that a limited amount of RCA may be associated with a slight improvement in the deformation capacity of the beams, allowing them to sustain larger deflections before failure. However, further increases in RCA content resulted in a noticeable reduction in energy absorption. This reduction may be associated with the relatively lower mechanical properties of recycled aggregates and weaker ITZ characteristics, which can promote earlier crack propagation and reduce the post-peak deformation capacity of the beams [17, 25].

A slightly different trend can be observed for the rectangular beams, where the energy absorption tends to decrease as the RCA replacement ratio increases, without the initial improvement observed in the square beams. The presence of old mortar attached to recycled aggregates increases the porosity of the concrete and weakens the aggregate–paste bond, which consequently reduces the structural capacity and deformation performance of the beams [12, 23].

It can also be observed that square beams generally absorb more energy than rectangular beams, particularly at lower RCA replacement ratios, which may be related to the more uniform stress distribution within the square cross-section. This observation is consistent with the previously discussed load–deflection behavior, where specimens exhibiting larger

midspan deflections and higher deformation capacity generally showed greater energy absorption.

4. NUMERICAL MODELING

4.1 Finite element model

A three-dimensional finite element model was developed using ABAQUS to simulate the structural behavior of the tested reinforced concrete beams, as shown in Figure 9. The nonlinear analysis was performed using the static general procedure with displacement-controlled loading to ensure stable convergence during the post-peak response [26].

Concrete was modelled using eight-node linear brick elements with reduced integration (C3D8R), which are widely used for nonlinear analysis of reinforced concrete members due to their computational efficiency and capability to capture cracking and crushing behavior [26, 27].

The reinforcing bars were represented using two-node truss elements (T3D2), which are suitable for modeling axial force transfer in reinforcing steel [27, 28].

The interaction between concrete and reinforcing bars was defined using the embedded region technique, assuming a perfect bond between steel and surrounding concrete. Although this assumption does not explicitly account for local bond-slip effects, the adopted modelling approach provided satisfactory agreement with the experimental response of the tested beams in terms of overall structural behavior and failure mode. This approach allows the reinforcement to share the displacement field of the host concrete elements without explicitly defining the bond interaction between steel and concrete.

To simulate the experimental loading conditions, steel loading and support plates were modelled to ensure a uniform distribution of the applied displacement and to avoid unrealistic stress concentrations at the contact regions [26]. A structured mesh was generated for the concrete domain with an average element size of approximately 20 mm, providing a balance between computational efficiency and solution accuracy [27].

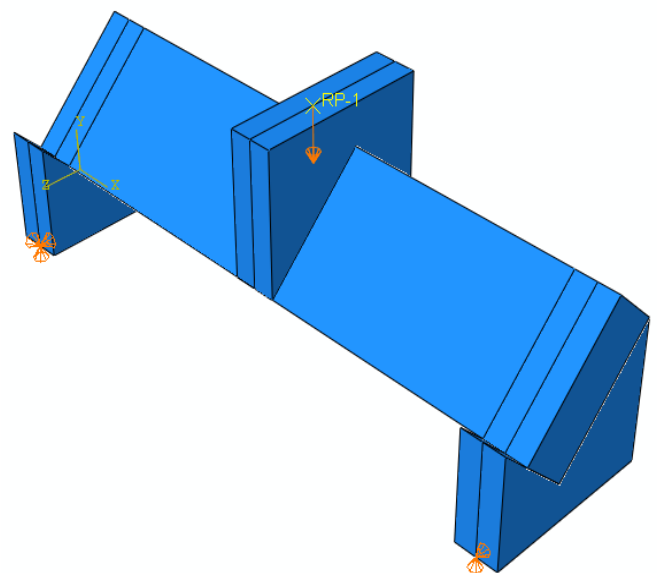


Figure 9. Finite element model of the reinforced concrete beam in ABAQUS

Table 3. Concrete Damaged Plasticity (CDP) parameters

Parameter	Value
Dilation angle ψ	25
Eccentricity ε	0.1
Biaxial to uniaxial compressive strength ratio (f_{b0}/f_{c0})	1.16
(Kc)	0.667
Viscosity parameter μ	0.001

4.2 Material properties

The material properties adopted in the numerical model were based on the experimental results obtained from the tested concrete mixtures. Four concrete mixes corresponding to RCA replacement ratios of 0%, 30%, 50%, and 75% were considered, and the measured compressive and split tensile strengths were used to define the concrete behavior in the model. The nonlinear behavior of concrete was simulated using the Concrete Damaged Plasticity (CDP) model in ABAQUS. The compressive and tensile responses were defined using stress–strain relationships for concrete in compression and tension derived from the experimentally measured compressive strength, split tensile strength, and modulus of elasticity of the tested concrete mixtures. Established empirical formulations reported in the literature were adopted to represent the nonlinear behavior of concrete. In addition, the corresponding compression and tension damage parameters were incorporated to account for stiffness degradation associated with concrete cracking and crushing [28, 29]. The reinforcing steel was modelled using an elastic–perfectly plastic constitutive law, assuming linear elastic behavior up to the yield stress followed by a perfectly plastic response [26]. In addition, the reinforcement layout in the numerical model was defined to match the experimental specimens, including the number of bars, their diameters, and their distribution within the beam cross-section.

The main parameters defining the CDP model are summarized in Table 3 [27].

4.3 Boundary conditions

The boundary conditions adopted in the numerical model were defined to reproduce the experimental test setup as closely as possible. The beams were modelled under simply supported conditions, consistent with the laboratory tests. Steel plates were introduced at the loading and support regions and assigned elastic steel properties to ensure a uniform distribution of stresses and to avoid unrealistic stress concentrations at the contact zones [26].

The interaction between the concrete beam and the steel plates was modelled using a surface-to-surface contact approach, allowing a more realistic representation of the interface behavior. This formulation enables proper load transfer while accounting for friction and possible separation between the contacting surfaces [26, 28, 30].

The external load was applied at the midspan of the beam using displacement control through the loading plate, allowing the nonlinear response of the beam to be captured up to failure [2].

4.4 Mesh sensitivity

Meshing refers to the discretization of the numerical model into a finite number of elements to approximate the structural response. The accuracy and stability of the finite element

analysis are influenced by the adopted mesh density; therefore, selecting an appropriate mesh size is important for achieving stable and accurate numerical results [30, 31].

In this study, a mesh sensitivity study was conducted using element sizes of 15 mm, 20 mm, and 25 mm to evaluate the influence of mesh refinement on the numerical response. Based on the obtained results, an element size of 20 mm was selected, as it provided a good balance between numerical accuracy and computational efficiency. Further mesh refinement did not lead to significant changes in the global response of the beams [30]. The mesh sensitivity assessment in the present study was primarily focused on the global structural response and load–deflection behavior of the beams.

4.5 Numerical results

4.5.1 Numerical load capacity and load–deflection behavior

The load-carrying capacity of the beams was evaluated in terms of the P_{cr} and P_u obtained from the finite element analysis. These results are summarized in Table 4 and compared with the experimental findings to assess the accuracy of the numerical model and its ability to capture the shear behavior of recycled aggregate concrete beams under biaxial loading.

The comparison between the numerical and experimental results presented in Table 4 indicates that the finite element model provides a reasonable prediction of both the cracking load and P_u for all beam specimens. For the cracking load, the numerical-to-experimental ratios ranged approximately between 0.84 and 0.95, showing that the model generally tends to slightly underestimate the cracking load, particularly at higher RCA replacement levels. This behavior may be associated with the sensitivity of crack initiation to local material heterogeneity and tensile properties, which are difficult to capture precisely in numerical simulations. In terms of P_u , the numerical predictions showed good agreement with the experimental results, with ratios ranging between 0.88 and 1.13. The model demonstrated a consistent ability to capture the shear capacity of both square and rectangular beams.

Table 4. Comparison of load capacities obtained from experimental tests and finite element analysis

Beam ID	P_{cr} , FE kN	P_{cr} , Exp. kN	$\frac{P_{cr, FE}}{P_{cr, Exp.}}$	P_u , FE kN	P_u , Exp. kN	$\frac{P_u, FE}{P_u, Exp.}$
SQ-0	36	40	0.90	155	136.8	1.13
SQ-30	30	34.34	0.87	144	158.8	0.91
SQ-50	21	25	0.84	124	137.65	0.9
SQ-75	17	20	0.85	98	105.75	0.93
RE-0	32	35	0.92	151	149.9	1.007
RE-30	32	34.34	0.92	128	126	1.01
RE-50	17	20	0.85	95	108	0.88
RE-75	19	20	0.95	100	99.25	1.007

Note: SQ = square beams; RE = rectangular beams; FE = finite element analysis; Exp. = experimental test; P_{cr} = first-crack load; P_u = ultimate load.

Overall, the results indicate that the developed finite element model is capable of reasonably predicting the load-carrying capacity of recycled aggregate concrete beams, particularly in terms of P_u response.

The load–deflection curves shown in Figure 10 and Figure 11 illustrate the general behavior of the rectangular and square beams obtained from both experimental and numerical results. In general, the response can be divided into three main stages. In the first stage, a nearly linear relationship is observed,

representing the elastic behavior before cracking. This is followed by a nonlinear stage initiated by the formation of the first-cracks, where a gradual reduction in stiffness occurs. The final stage corresponds to the approach to P_u , where deflection increases with a reduced rate of load increment until failure.

A good agreement in the overall shape and response stages can be observed between the numerical and experimental curves for both beam types. Although slight differences in deflection values exist, the general trend and progression of the curves indicate that the finite element model is capable of capturing the structural behavior with reasonable accuracy. The comparison between the numerical and experimental results was primarily focused on the overall structural response and global load–deflection behavior rather than detailed local crack width and crack spacing prediction.

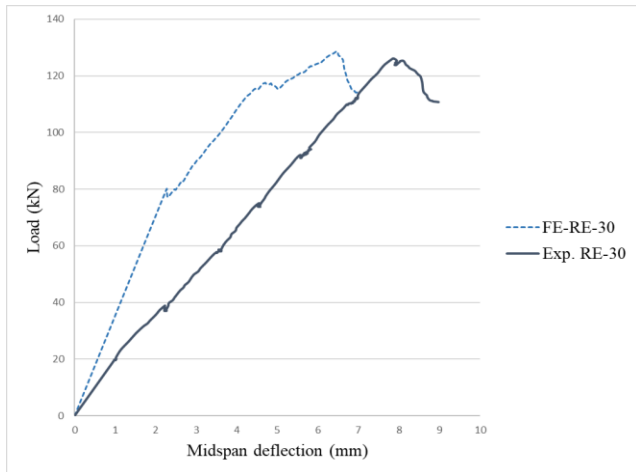


Figure 10. Comparison of experimental and numerical load–deflection curves for RE-30 beam
Note: RE: rectangular beams.

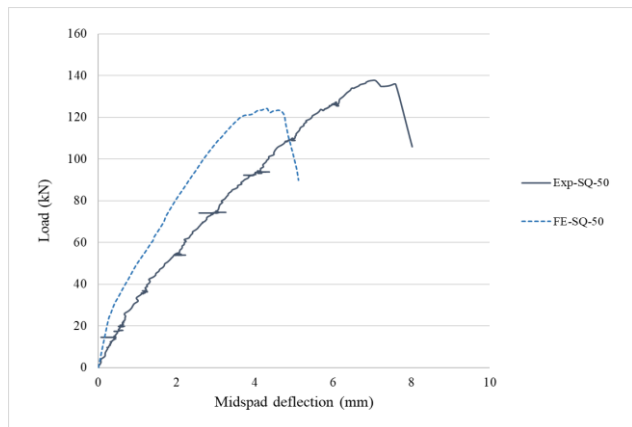


Figure 11. Comparison of experimental and numerical load–deflection curves for SQ-50 beam
Note: SQ: square beams.

4.5.2 Numerical crack patterns

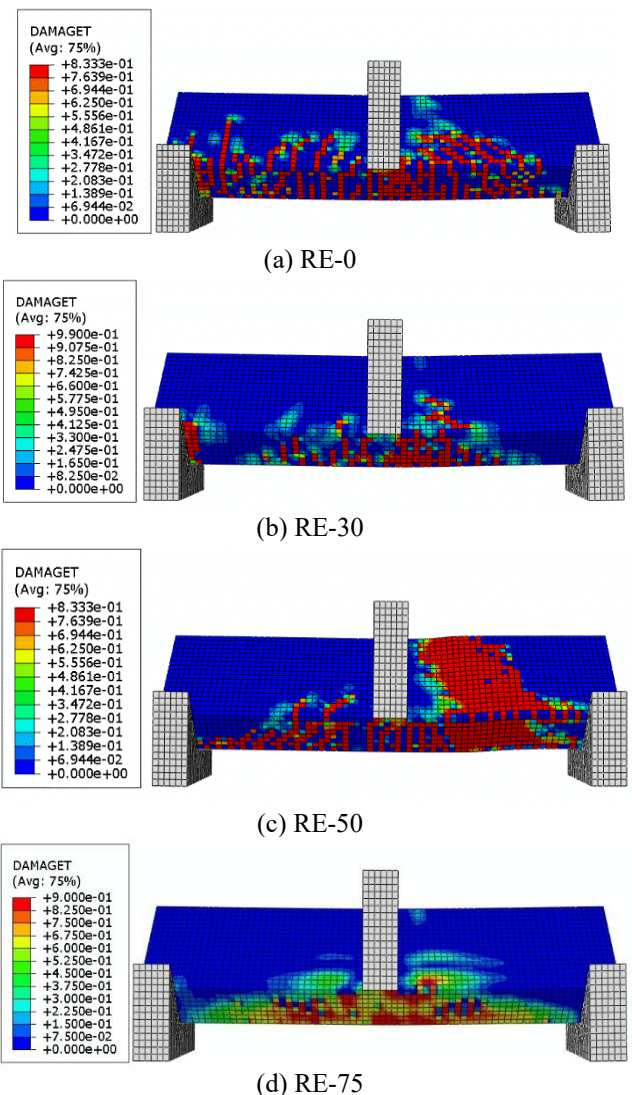
The tensile damage contours (DAMAGET) predicted by the finite element model are presented in Figure 12 for all beam specimens. In the ABAQUS simulations, the DAMAGET variable was used as an indicator of tensile damage development and probable crack localization zones within the concrete. The results suggest that tensile damage initiated near the bottom tension region of the beams and progressively localized along inclined paths toward the loading region, indicating the likely formation of dominant diagonal cracking

zones.

The predicted tensile damage localization patterns showed good agreement with the experimental observations presented in Figure 4, where similar diagonal shear cracking regions were observed extending between the support and loading zones. Although the numerical results do not directly represent physical crack widths or exact crack trajectories, they provide a reasonable indication of the regions where cracking is likely to develop under the applied loading conditions.

Furthermore, the numerical results indicated that increasing the RCA replacement ratio was generally associated with a wider and more continuous tensile damage zone, which may reflect the lower stiffness and tensile strength characteristics of recycled aggregate concrete. Despite these variations, the overall failure mode remained similar for both rectangular and square beams, indicating that the finite element model was able to reasonably capture the dominant shear failure mechanism observed experimentally. This behavior was characterized by progressive localization of tensile damage along inclined paths with limited deformation prior to failure, which is consistent with a shear-dominated brittle response.

In addition, the distribution of maximum principal plastic strain (PE, Max. Principal), as shown in Figure 13, provided further indication of strain localization within the shear span. The concentration of plastic strain along inclined bands supports the observed shear transfer mechanism and identifies regions susceptible to crack development, without directly representing actual crack widths or crack openings.



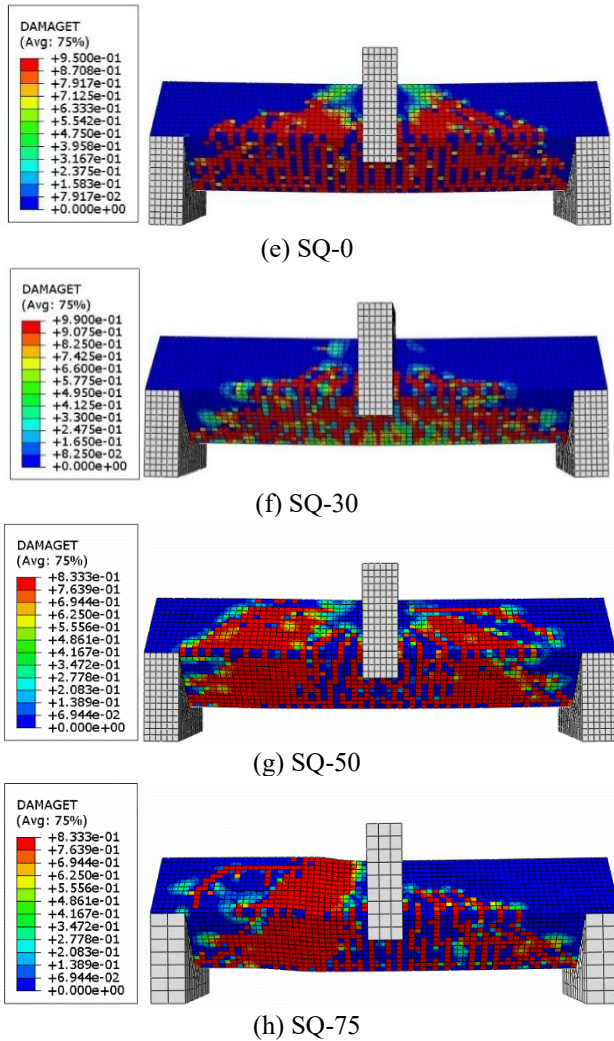


Figure 12. Tensile damage contours (DAMAGET) predicted by the finite element model for beams subjected to 45° loading: (a) RE-0, (b) RE-30, (c) RE-50, (d) RE-75, (e) SQ-0, (f) SQ-30, (g) SQ-50, and (h) SQ-75
Note: RE: rectangular beams; SQ: square beams.

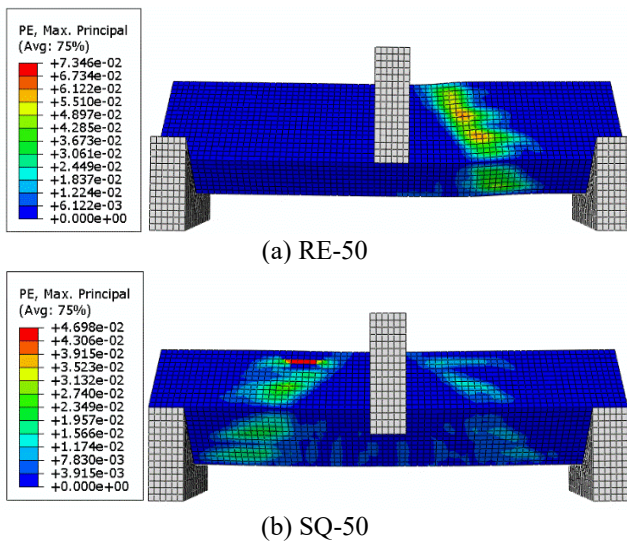


Figure 13. Distribution of maximum principal plastic strain indicating strain localization zones in the tested beams: (a) RE-50 and (b) SQ-50
Note: RE = rectangular beam; SQ = square beam; PE, Max. Principal = maximum principal plastic strain.

5. CONCLUSIONS

The principal conclusions of the present study can be summarized as follows:

- (1) All tested beams exhibited a shear-dominated failure indicated by the formation of a noticeable diagonal crack extending between the support and loading regions under biaxial loading at an inclination of 45°.
- (2) Increasing the RCA replacement ratio was generally associated with a reduction in cracking load. Although a slight increase in the P_u was observed at the 30% RCA replacement level, the P_u generally decreased at higher replacement ratios, indicating an overall reduction in shear capacity.
- (3) The development and propagation of diagonal cracks became more pronounced with increasing RCA replacement ratio, while wider and more continuous cracking patterns were observed at higher replacement levels, reflecting the lower stiffness and tensile resistance of recycled aggregate concrete.
- (4) The load–deflection response exhibited a reduction in structural stiffness with increasing RCA content; nonetheless, the ultimate deflection remained relatively limited due to the brittle nature of shear failure.
- (5) The effect of cross-sectional geometry on the failure mode was limited, although rectangular beams exhibited relatively higher stiffness compared with square beams.
- (6) Within the investigated experimental conditions and based on the limited number of tested specimens, recycled aggregate concrete beams incorporating RCA replacement ratios up to 50% showed structural behavior generally comparable to the control specimens under the considered 45° loading configuration.
- (7) The finite element model developed using ABAQUS and the CDP model provided reasonable predictions of the P_u , overall structural response, and tensile damage localization patterns of the tested beams, demonstrating its capability to simulate the shear behavior of recycled aggregate concrete beams under the investigated loading conditions.

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