

Effect of Cross-Section Shape on RC Specimen's Behavior Under Asymmetrical Impact Loading



Khalil Al-Bukhaiti, Liu Yanhui, Zhao Shichun, Han Daguang,
and Hussein Abas

Abstract By applying asymmetrical lateral impact forces on RC specimens, the specimens' cross-sectional shape is analyzed. The effectiveness of the RC specimens' resistance to impact was examined using a drop hammer. Performing research on the factors that led to the failure of various RC specimen shapes and the dynamic responses they exhibited. In the experiment, eight circular and square specimens were used. Includes the method of failure, the impact force, and the deflection time history. The findings point to shear fractures between the point of impact and the adjacent support. The right side of the impact point has suffered significant damage, and the shear tests on all specimens failed. The peak impact force that square specimens can bear may be greater than circular ones. Protecting the concrete core and reducing maximum deflection are benefits of using a square specimen. When the ratio of stirrups is raised, there is only a little variation in the square specimen's damage range. This may cause a slight reduction in damage, but it is not significant. The plateau force of a circular specimen can be increased, but only a little. An increase in the stirrup ratio may increase energy use.

Keywords Asymmetrical impact · Absorbed energy · Shear fractures

K. Al-Bukhaiti · L. Yanhui (✉) · Z. Shichun · H. Abas
School of Civil Engineering, Southwest Jiaotong University, Chengdu 310061, Sichuan, China
e-mail: yhliu@swjtu.edu.cn

K. Al-Bukhaiti
e-mail: eng.khalil670@hotmail.com

H. Daguang
Faculty of Civil Engineering, Southeast University, Nanjing 210096, China

1 Introduction

Reinforced concrete structures occupy most of the existing building structures in the world. Most reinforced concrete buildings have been in service for more than 30 years. At the same time, many reinforced concrete structures built before the 1950s are still in use in many European and American countries, including many transportation infrastructures [1]. Many reinforced concrete structures, especially those for civil infrastructure, have been in service beyond their usefulness. Reinforced concrete structures built for many years generally suffer from corrosion of steel reinforcement, cracking, and spalling of concrete [2]. These structures often carry loads higher than their maximum design-bearing capacity. The requirements for the seismic performance of structures also increase the need for reinforcement and repair buildings that have been in service for a long time [3–6]. Based on the above reasons, many scholars are devoted to exploring an economical technology capable of strengthening and repairing structures, which has made great progress in strengthening and repairing reinforced concrete structures in recent years. Since the beginning of the new century, infrastructure construction in China has grown rapidly, and reinforced concrete (RC) structure is one of the main structural forms. Due to their good mechanical properties and economy, RC components are widely used in bridges, urban underground spaces, and building structures. They are often used as load-bearing components of structures. During service and use, RC members may be impacted by automobiles, derailed trains, and airplanes. Suppose the impact resistance of RC members is weak or lacks impact resistance. In that case, the damage may have a catastrophic impact on the overall structure, resulting in huge economic losses and heavy casualties. In recent years, with the advancement of urban construction, more and more accidents have occurred due to the impact of building structures. For example, the JR train derailment accident in Japan [7] caused damage to buildings along the track, and many people died; the German high-speed rail derailment accident [8] caused the concrete bridge above the track to collapse. Accidents of ships hitting bridges have also occurred in Jiujiang Bridge piers, China, as shown in Fig. 1 according to the (http://www.chinadaily.com.cn/china/2007-06/15/content_895374.htm) Chinese net news website [9]. In impact accidents, RC members will show failure modes such as bending, shearing, and punching [10], as shown in Fig. 2.

Similar to static loading conditions, reinforced concrete (RC) members under impact loading will exhibit two failure modes: bending failure and shear failure [12]. After the plastic hinge is formed at the position where the member reaches the ultimate moment bearing capacity, the member undergoes bending failure. This failure mode has good flexibility and can absorb more impact energy during impact [13]. Contrary to the bending failure mode, the shear failure mode is brittle, and the component resistance cannot reach the ultimate bending moment capacity. This failure mode has poor flexibility, leading to premature failure of the component, which will seriously reduce the impact resistance of the component. However, the behavior of RC members under impact loading differs from that under static loading



Fig. 1 Accidents of ship on RC piers of Jiujiang Bridge in China [9]

Fig. 2 Partial diagram of failure of RC member under impact [10, 11]



conditions. The impact load will cause the material's strain rate effect, the component's inertial force, and the local effect caused by the impact load. The static test cannot reflect the impact resistance of the RC component under the impact load. Experimental studies have shown that: RC beams fail in bending under static conditions, but shear failure occurs under impact loads [14]. RC beams under impact loads may exhibit more localized damage (such as punching shear damage) [15, 16]. Therefore, there have been some experimental studies at home and abroad to explore the behavior characteristics of RC components under impact loads. Khalil et al. (2021) [17] conducted experimental research on the bearing capacity of ordinary concrete and CFRP-strengthening concrete columns after the impact. The RC column and the other four reinforced columns were placed under the same impact load in the test.

Then the static axial loading test was carried out on the impact-damaged column to obtain the remaining bearing capacity of the impact-damaged column to evaluate the effectiveness of different strengthening measures. The test results show that adding CFRP layers of energy-dissipating materials can improve the post-impact bearing capacity. The strength, deformation, elasticity, and confining effect of members can be affected by changes in cross-sections, reinforcements, and width-to-thickness ratios [18–21]. Recently, there have been a lot of studies that have a deep discussion of the effect of asymmetrical lateral impact load on RC specimens with and without FRP-strengthening materials [22–26]. Consequently, research on the failure mode and force parameters of cross-section shape RC specimens is limited. Furthermore,

the study investigated the dynamic behavior of RC specimens using asymmetrical-span drop hammer impact testing. The main focus of the study is on the typical failure mode caused by an asymmetrical span drop hammer, the time history curve of deflection and impact force, and the effect of different cross-section shapes on RC specimens.

2 Materials and Methods

In the impact test, eight reinforced concrete specimens will have square and circular cross-sections. The test was conducted using a DHR-9401 drop hammer impact tester from the Taiyuan University of Technology. Using Chinese Pinyin initials, “F” represents square members, “Y” represents circular members, and “H” represents concrete specimens. Each test specimen is poured with the same material to achieve interoperability. Asymmetrical lateral impact forces are applied to specimens with different impact heights, longitudinal reinforcement ratios, and stirrup ratios to determine impact resistance. The specimen is supported at both ends, has a design length of 1500 mm, and supports lengths of 200 mm in the test. This collision is designed to mimic a collision between a high-speed railway locomotive and an RC column member. The impact point is located at 2/9 of the clear span, 200 mm from the right and 700 mm from the left. [27]. The cross-sectional dimension of the square specimen is 120 * 120 mm, while the diameter of the circular specimen is 114 mm. Figure 3 shows that square specimens contain 4 HRB235 steel bars, whereas circular specimens have 6 HRB235 steel bars evenly distributed along the ring direction. The stirrup has a diameter of 4 mm. The concrete cover thickness for square specimens is 20 mm, while for circular specimens is 12 mm.

The specimens’ dimensions, reinforcing details, and parameter factors are included in Table 1. Frictional energy loss is included in the impact energy depicted in the Table, which was calculated using energy conservation principles. Under the asymmetrical impact scenario, this study investigates the RC members’ failure mode, impact force, and deflection. Since the impact, members’ responses have been related to strain rate, confinement effects, and other train-specific factors. As a consequence, two impact scenarios and several reinforcement configurations were considered.

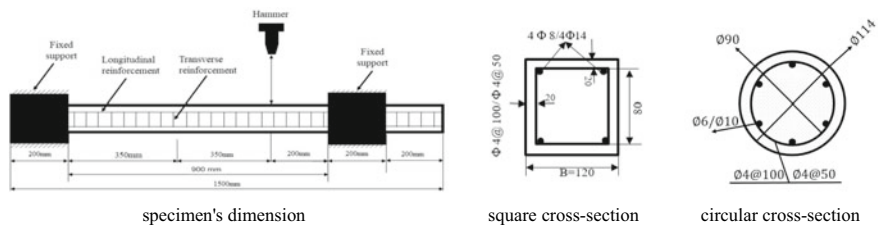


Fig. 3 The specimen’s schematic illustration

Table 1 Test specimen's design information

No.	Long. Reinf ratio	Volume stirrup ratio	Impact height (m) h	Impact velocity (m/s) $v = \sqrt{2gh}$	Impact energy (J) $E_{impact} = mgh$	Factors
FH1	2.01% (4 ϕ 8)	0.62% (ϕ 4@50)	1.0	4.42	2646	Height
FH2	2.01% (4 ϕ 8)	0.62% (ϕ 4@50)	2.0	6.26	5292	
FH3	6.16% (4 ϕ 14)	0.64% (ϕ 4@50)	2.0	6.26	5292	Long reinf ratio
FH4	2.01% (4 ϕ 8)	0.31% (ϕ 4@100)	2.0	6.26	5292	Stirrup ratio
YH1	1.67%(6 ϕ 6)	1.26% (ϕ 4@50)	1.0	4.42	2646	Height
YH2	1.67%(6 ϕ 6)	1.26% (ϕ 4@50)	2.0	6.26	5292	
YH3	4.61%(6 ϕ 10)	1.26% (ϕ 4@50)	2.0	6.26	5292	Long reinf ratio
YH4	1.67%(6 ϕ 6)	0.63% (ϕ 4@100)	2.0	6.26	5292	Stirrup ratio

2.1 Test Devise, Loading, and Measurement Scheme

The authors completed this impact test on the DHR9401 drop hammer impact-testing machine, as shown in Fig. 4. The DHR9401 drop hammer slideway height is 13.47 m, and the effective drop distance is 12.60 m. The test frame is a portal frame composed of two vertical lattice steel columns and rigid beams. The body falls smoothly, and the impact velocity of the drop hammer is very repeatable. The lower part of the support is fixed on the rigid platform, and a linear bearing is installed in the support. This bearing can restrain the displacement of the members in all directions except the axial direction to realize the boundary condition of fixed support. The impact hammer is made of (45# forged steel) and consists of three main elements, and the first element is a stiffened flat head constructed of large-strength chromium 15 (64HRC), which is a rectangular parallelepiped face, and the size is 80 mm $\times$ 30 mm $\times$ 80 mm. The striker's second element is the weight portion; this element contains the striker's main mass and provides a weight of (270) kg. The third element is that of load cells, which are used to calculate the impact force record. The impact hammer's total weight is 65 kg and could be lifted to the requisite height to generate varied velocities of impact (up to 15.7 m/s) and energy (see Fig. 4). A load cells sensor is placed between the impact head and the drop hammer to measure the impact force. The test specimen support is made of (Q235) steel and divided into upper and lower parts. Figure 4 shows a bolt connection between the upper and lower parts. The bolts provide pre-tightening force for the two parts of the support, effectively improving the friction between the support and the test specimen. It can restrain the specimens

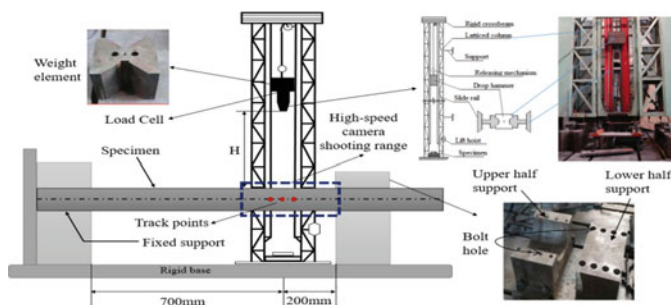


Fig. 4 Test equipment photos

from moving in the axial direction to a certain extent. A force sensor connects an impact head and drops a hammer for measuring the impact time-time history curve.

Data is collected at a million per second. The TDS420 dynamic data storage oscilloscope records and saves the strain amplifier signal. Furthermore, with a shooting frequency of 2500 frames/s, the high-speed camera in front of the specimen's impact site records the impact deformation and destruction process. A high-speed camera captures a deformation shot of the test specimen each 0.4 ms. Three-track white spots were marked on the specimen at 150 mm intervals to capture deformations (see Fig. 4). A collection of Microsoft Excel spreadsheets, Origin 19 pro, CAD design applications, and picture editing software handles the specimens' white spots data. Both qualitative and quantitative data were evaluated.

2.2 Material Properties

The concrete properties were measured using the “Standard for Test Methods of Mechanical Properties of Concrete” (GB50081-2010) on concrete cubes to determine the average compressive concrete strength. The quasi-static tensile tests on steel reinforcement bars were performed according to the “Metal Material Tensile Test Method” (GB/T228-2010) [28]. Table 1 summarizes the materials' properties and figures of testing procedures of materials (Table 2).

2.3 Details of Test and Analysis

The specimens are positioned in the impact test machine to demonstrate the structural specimen's dynamic response properties under the asymmetrical lateral impact (see Fig. 4). The specimen's compression zone concrete was shattered. Large bending

Table 2 Details on the materials of the test specimen

Materials		Parameters	Magnitude	Figure	
Concrete		Comp. strength f_c'	55MPa		
Reinforcement steel	$\varnothing 4mm$	Elastic modulus E_s	180GPa		
		Ultimate strength f_u	684MPa		
		Yield strength f_y	520 MPa		
		Elongation rate δ	0.213		
	$\varnothing 6mm$	Elastic modulus E_s	200GPa		
		Ultimate strength f_u	509 MPa		
		Yield strength f_y	380 MPa		
		Elongation rate δ	0.227		
	$\varnothing 10mm$	Elastic modulus E_s	188GPa		
		Ultimate strength f_u	412 MPa		
		Yield strength f_y	325 MPa		
		Elongation rate δ	0.224		

Cube uniaxial comp. test

Steel bar tensile test

fractures approach the compression zone. Once the ultimate deflection of the specimen exceeds 1.1% of the clear span, it is indicated that the specimen has failed related to bending.

3 Failure Modes

Figure 5 shows the final failure mode of specimens after impact load. It seems that all RC specimens have suffered a shear failure. Damaged concrete looks to have lost its bearing ability at impact. Arrows indicated the left support has flexural fractures, while the dotted line has a brittle shear failure. Observe how the drop height affects the RC specimens’ failure patterns. The 1 m hammer specimen had a shear failure at the impact point and a vertical fracture at the left support. The impact point’s bottom vertical crack did not propagate, but the support’s left and right vertical cracks developed. Figure 5-a shows brittle shear failure with significant concrete cracking and buckling of steel reinforcing bars in the diagonal crack zone. A larger longitudinal and transverse reinforcement ratio improve the impact resistance of specimens.

On the other hand, Fig. 5-b shows the total damage of circular cross-section specimens is rather high. Compared to square shape specimens, the steel bar is stretched whenever longitudinal reinforcement fails between the impact point and the failure surface. In the final failure mode, square specimens seem to have more bearing ability than circular specimens. In summary, the cross-sectional shape affects the distribution of contact damage, which controls the pattern of specimens’ failure and results in the difference between failure surfaces [29, 30].

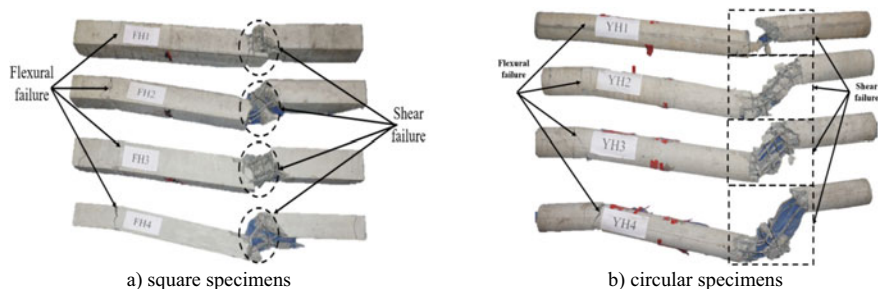


Fig. 5 Failure modes for specimens after the end of the impact test

4 Test Results and Discussion

4.1 Time History of Impact Load Analysis

Figure 6 illustrates an impact force-time history curve that may be separated into different stages; a triangle pulse is produced by contacting the impact body with the specimen at zero time. In the stable stage, the impact force varies within a particular range and lasts for a significant duration. The impact force begins to attenuate after a steady stage and reaches zero. The peak impact force for square shape specimens is focused between 294 and 486kN in less than a second (4 ms), while circular shape specimens are concentrated between 209 and 305kN in less than a second (2 ms). FH1 and YH1 have the least impact force once compared to other specimens due to their lower impact height. The deformation of the specimens transfers and dissipates a large amount of kinetic energy. The peak impact force for specimen FH2, notable compared to other specimens, increases as impact velocity increases with stable fluctuations on the plateau value. This observation is consistent with prior impact test patterns in previous studies [31, 32]. Simultaneously, increasing impact height for YH2 might result in a lower plateau value and shorter impact duration. In the plateau stage, increasing the longitudinal reinforcement had a limited effect on the plateau impact force for FH3. Still, it enhanced the peak impact force and improved the plateau value for YH3. With extended impact duration in consideration, increasing the stirrup ratio causes a violently fluctuating plateau value for FH4 with a minimal influence on the peak impact value, which differs from prior studies [33, 34]. By increasing the peak impact force and decreasing the plateau value for YH4, the stirrup ratio has a greater influence on strengthening the specimen's stiffness than the reinforcement ratio.

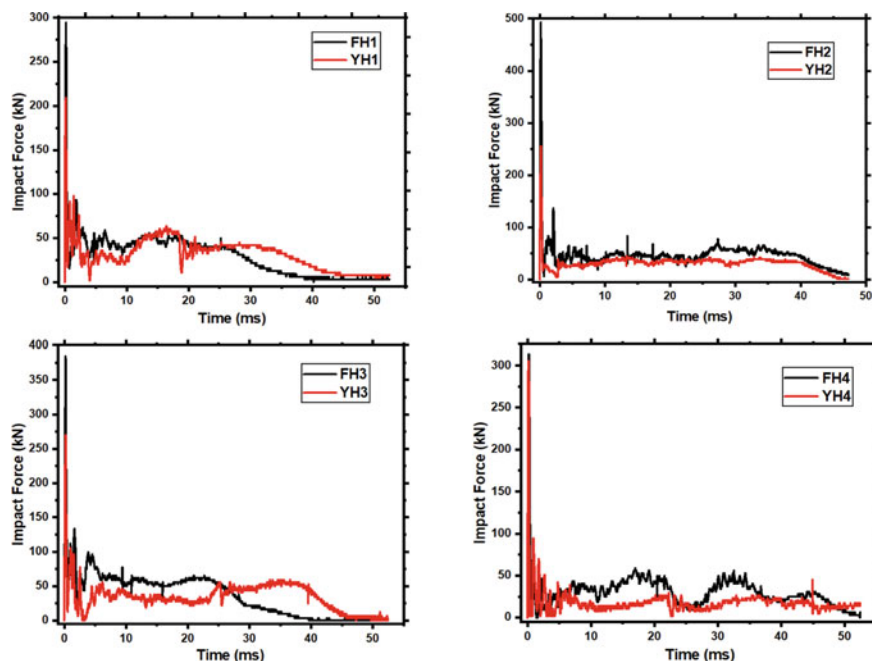


Fig. 6 Impact force time history curves

4.2 Time History of Deflection Analysis

Deflection time history curves were calculated by tracking the specimen's middle three spots with the high-speed camera (see Sect. 2.1, Fig. 4). The deflection data collected by the impact body starts once it contacts the specimen and ends when it stops falling. The deflection time history curves for specimens are shown in Fig. 7. There are two distinct stages in the vertical deflection curve of square shape specimens. The deflection increases from zero to the maximum value during the loading stage, then drops from the maximum to the residual value during the unloading stage. While there is just one stage (loading stage) in which the deflection goes from zero to the maximum value for circular shape specimens, data will be lost in the later stage owing to the concrete fragments collapsing. Table 3 summarizes the impact, deflection, and duration findings for square and circular shape specimens.

For the FH2 specimens, both the peak and residual deflection increase with the drop hammer height. With the same reinforcing configuration, impact height affects deflection rates for YH2. As shown on the FH3 specimen, the reinforcement ratio improves the members' lateral stiffness, which was observable during the loading stage. Deflection change for YH3 is decreased and slowed by increasing the reinforcement ratio. The maximum deflection is slowed when the stirrup ratio is increased. The YH4 deflection value is increased by damaged concrete between the impact

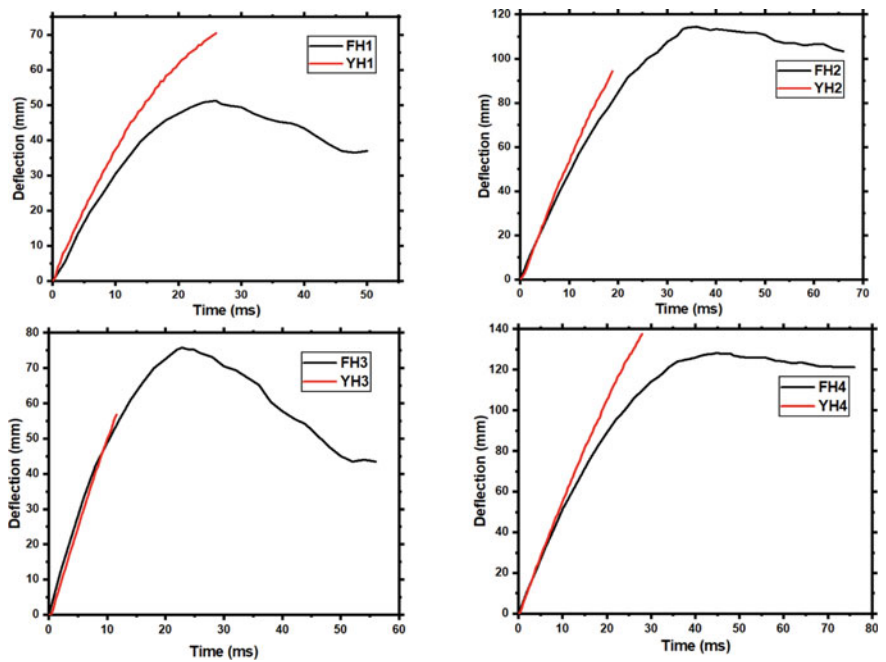


Fig. 7 Deflection time history curves

Table 3 Test specimen results collected from experimental outcomes

No	$F_{peak}(kN)$	$F_{plateau}(kN)$	$t_d(ms)$	$\Delta(mm)$
FH1	294.5	30.23	50	51.18
FH2	493	83.54	53	117.4
FH3	376	12.32	52	76.3
FH4	315	22.34	51	128.2
YH1	209.30	39.55	30	70.39
YH2	255.30	34.18	37	94.30
YH3	269.77	40.16	35	56.77
YH4	305.43	16.20	42	137.55

point and the right-end support. Compared to other specimens, the negative bending fracture of the YH4 distant bearing is practically penetrated, which differs from prior studies [35, 36]. Compared to previous specimens, the FH4 and YH4 impact specimens deflect significantly.

4.3 Effect of Cross-Section Shape

Figure 8 shows the impacts of various shapes cross-sections on peak impact force, plateau, duration, and deflection for the specimen parameters listed in Table 1 (see Sect. 2). The square specimen FH2 with an impact height of 2 m has the largest peak impact force because its squaring shape protects the concrete core body, as shown in Fig. 8-a. Since it transmits and dissipates much kinetic energy, the circular specimen YH1 with an impact height of 1 m has the least peak impact force. Simultaneously, Fig. 8-b shows the effect of plateau force on the specimens' shape cross-section. Although increasing the longitudinal reinforcement ratio had a limited influence on the plateau force, square specimen FH3 with a high longitudinal reinforcement ratio had the least plateau force. YH3's peak impact force and plateau value were improved as a result. At the same time, the plateau values for square specimen FH2 improve as the impact velocity increases. Due to the concrete collapsing of circular specimens, which have a smaller peak impact force and bearing capacity than square specimens. As seen in Fig. 8-c, the impact duration, square-shaped cross-section specimens consume longer than circular specimens during the impact period [37, 38]. As Fig. 8-d illustrates for specimen FH2, increasing impact velocity creates maximum deflection. The YH4 and FH4 distant bearings' negative bending fractures have been almost penetrated. As a result, increasing the stirrups ratio does not affect the deflection value for square and circular specimens [39].

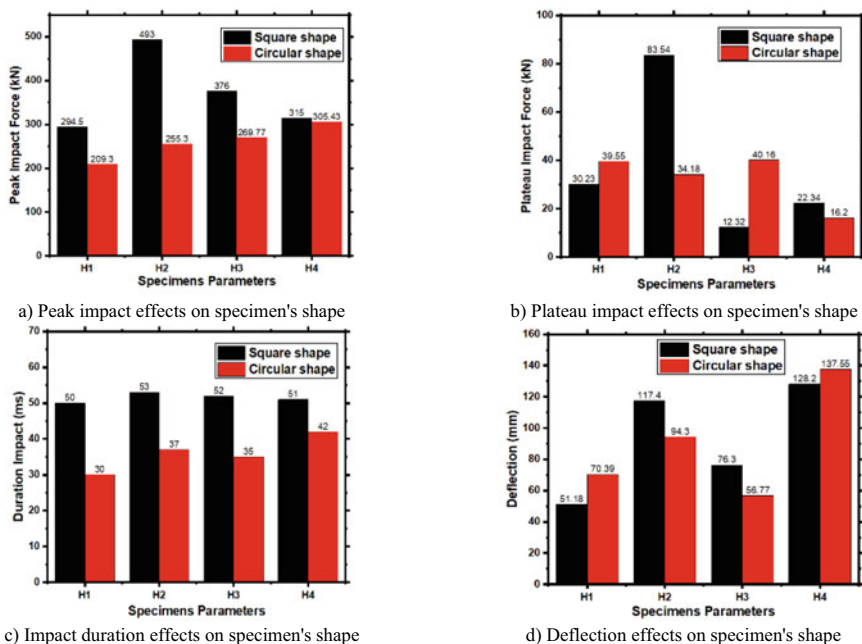


Fig. 8 Effect of specimen's shape cross-section

5 Conclusion

The experimental work on RC square and circular shape cross-section specimens under asymmetrical lateral impact loads was summarized in this study. The impact height, reinforcement, and stirrups ratio were investigated and explored. These factors have been compared in terms of (impact force and deflection record). Both square and circular-shaped RC specimens subjected to asymmetrical impact loading conditions tend to fail brittle, with diagonal cracks extending from the impact point down the right support. The drop hammer height affects crack width early in the impact stages for square shape specimens. The stirrups reinforcement ratio was one of the most important factors influencing square RC specimens' performance and failure mode. The results of this experiment demonstrated that decreasing the stirrups reinforcement spacing from 100 to 50 mm improves the stiffness of the circular shape specimen. The increased passive pressure from the stirrups then decreases the concrete's overall and local failure. Thereby minimizing the maximum deflection of the square shape specimens by 8.5%. In addition, longitudinal reinforcement greatly protects the concrete core and mitigates the specimen's maximum deflection of both shapes. The experimental outcomes presented in this work showed an increase in longitudinal reinforcement for square shape specimens from (2.01%) to (6.16%), indicating an increase in crack numbers. Simultaneously, these cracks' width is smaller in square shape specimens than in circular shapes containing a high longitudinal reinforcement ratio, resulting in a decrease in the maximum deflection of the square RC specimens by 41.5%.

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References

1. Tunc G, Tunc TE (2022) Engineering the public-use reinforced concrete buildings of Ankara during the Early Republic of Turkey, 1923–1938. *Endeavour* 46(3):100832. <https://doi.org/10.1016/J.ENDEAVOUR.2022.100832>
2. Bertolini L, Carsana M, Gastaldi M, Lollini F, Redaelli E (2011) Corrosion assessment and restoration strategies of reinforced concrete buildings of the cultural heritage. *Mater Corros* 62(2):146–154. <https://doi.org/10.1002/MACO.201005773>
3. Manfredi V, Masi A (2018) Seismic strengthening and energy efficiency: towards an integrated approach for the rehabilitation of existing RC buildings. *Buildings* 8(3):36. <https://doi.org/10.3390/BUILDINGS8030036>
4. Harrington CC, Liel AB (2021) Indicators of improvements in seismic performance possible through retrofit of reinforced concrete frame buildings. *Earthq Spectra* 37(1):262–283. https://doi.org/10.1177/8755293020936707/ASSET/IMAGES/LARGE/10.1177_8755293020936707-FIG4.JPEG

5. Joseph R, Mwafy A, Alam MS (2022) Seismic performance upgrade of substandard RC buildings with different structural systems using advanced retrofit techniques. *J Build Eng* 59:105155. <https://doi.org/10.1016/J.JOBE.2022.105155>
6. Villar-Salinas S, Guzmán A, Carrillo J (2021) Performance evaluation of structures with reinforced concrete columns retrofitted with steel jacketing. *J Build Eng* 33:101510. <https://doi.org/10.1016/J.JOBE.2020.101510>
7. Niwa Y (2009) A proposal for a new accident analysis method and its application to a catastrophic railway accident in Japan. *Cogn Technol Work* 11(3):187–204. <https://doi.org/10.1007/S10111-008-0112-5/FIGURES/13>
8. Solomon B (2003) Electric Locomotives
9. China Daily: Bridge Collapses in Collision with Boat (2007). <http://www.china.org.cn/english/China/214086.htm>. Accessed 7 Feb 2023
10. Cao R, El-Tawil S, Agrawal AK, Xu X, Wong W (2019) Behavior and design of bridge piers subjected to heavy truck collision. *J Bridge Eng* 24(7):04019057. [https://doi.org/10.1061/\(ASCE\)BE.1943-5592.0001414](https://doi.org/10.1061/(ASCE)BE.1943-5592.0001414)
11. Buth CE (2009) Analysis of large truck collisions with bridge piers: phase 1. Report of guidelines for designing bridge piers and abutments for vehicle collisions. <https://static.tti.tamu.edu/tti.tamu.edu/documents/9-4973-1.pdf>. Accessed 13 Feb 2023
12. Ho CM (2003) Inelastic design of reinforced concrete beams and limited ductile high-strength concrete columns. The University of Hong Kong (Pokfulam, Hong Kong). https://doi.org/10.5353/TH_B2750030
13. Thilakarathna HMI (2010) Vulnerability assessment of reinforced concrete columns subjected to vehicular impacts. Queensland University of Technology
14. Saatci S, Vecchio FJ (2009) Effects of shear mechanisms on impact behavior of reinforced concrete beams. *Struct J* 106(1):78–86. <https://doi.org/10.14359/56286>
15. Roehm C, Sasmal S, Novák B, Karusala R (2015) Numerical simulation for seismic performance evaluation of fibre reinforced concrete beam–column sub-assemblages. *Eng Struct* 91:182–196. <https://doi.org/10.1016/J.ENGSTRUCT.2015.02.015>
16. Fan W, Liu Y, Liu B, Guo W (2016) Dynamic ship-impact load on bridge structures emphasizing shock spectrum approximation. *J Bridge Eng* 21(10):04016057. [https://doi.org/10.1061/\(ASCE\)BE.1943-5592.0000929](https://doi.org/10.1061/(ASCE)BE.1943-5592.0000929)
17. Al-Bukhaiti K, Yanhui L, Shichun Z, Abas H, Aoran D (2021) Dynamic equilibrium of CFRP-RC square elements under unequal lateral impact. *Materials* 14(13):3591. <https://doi.org/10.3390/ma14133591>
18. Liu Y, Al-Bukhaiti K, Abas H, Shichun Z (2020) Effect of CFRP shear strengthening on the flexural performance of the RC specimen under unequal impact loading. *Adv Mater Sci Eng* 2020:1–18. <https://doi.org/10.1155/2020/5403835>
19. AL-Bukhaiti K, Yanhui L, Shichun Z, Abas H (2022) CFRP strengthened reinforced concrete square elements under unequal lateral impact load, pp 1377–1387. https://doi.org/10.1007/978-3-030-91877-4_157
20. Abas H, Yanhui L, Al-Bukhaiti K, Shichun Z, Aoran D (2021) Experimental and numerical study of RC square members under unequal lateral impact load. *Struct Eng Int* 1–18. <https://doi.org/10.1080/10168664.2021.2004976>
21. Liu Y, Dong A, Zhao S, Zeng Y, Wang Z (2021) The effect of CFRP-shear strengthening on existing circular RC columns under impact loads. *Constr Build Mater* 302:124185. <https://doi.org/10.1016/J.CONBUILDMAT.2021.124185>
22. AL-Bukhaiti K et al (2022) Experimental study on existing RC circular members under unequal lateral impact train collision. *Int J Concr Struct Mater* 16(1):1–21. <https://doi.org/10.1186/s40069-022-00529-5>
23. Al-Bukhaiti K, Yanhui L, Shichun Z, Abas H (2022) Dynamic simulation of CFRP-shear strengthening on existing square RC members under unequal lateral impact loading. *Struct Concr*. <https://doi.org/10.1002/suco.202100814>
24. Yanhui L et al (2022) Comparative study on dynamic response of square section RC-members and CFRP-reinforced members under unequal transverse impact loading, vol 201. https://doi.org/10.1007/978-981-16-6932-3_12

25. Yanhui L et al (2022) Experimental and numerical study on unequal lateral impact behavior of Circular RC and CFRPRC components. In: IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report
26. Yanhui L et al (2022) Failure mechanism analysis of circular CFRP components under unequal impact load. *Structurae* 22:1668–1676. <https://doi.org/10.2749/NANJING.2022.1668>
27. Kang XJ, Liu YH, Zhao L, Yu ZX, Zhao SC, Tang H (2019) Dynamic response analysis method for the peak value stage of concrete-filled steel tube beams under lateral impact. *Adv Steel Constr* 15(4):329–337. <https://doi.org/10.18057/IJASC.2019.15.4.4>
28. GB/T 228.1-2010: Translated English of Chinese Standard
29. Zhang C, Lin H, Qiu C, Jiang T, Zhang J (2020) The effect of cross-section shape on deformation, damage and failure of rock-like materials under uniaxial compression from both a macro and micro viewpoint. *Int J Damage Mech* 29(7):1076–1099. <https://doi.org/10.1177/1056789520904119>
30. AL-Bukhaiti K et al (2023) Failure mechanism and static bearing capacity on circular RC members under asymmetrical lateral impact train collision. *Structures* 48:1817–1832. <https://doi.org/10.1016/J.ISTRUC.2023.01.075>
31. Saatci S, Vecchio FJ (2009) Effects of shear mechanisms on impact behavior of reinforced concrete beams. *ACI Struct J*. https://www.researchgate.net/publication/279897771_Effects_of_Shear_Mechanisms_on_Impact_Behavior_of_Reinforced_Concrete_Beams. Accessed 09 Feb 2021
32. Fan W, Yuan WC (2014) Numerical simulation and analytical modeling of pile-supported structures subjected to ship collisions including soil-structure interaction. *Ocean Eng* 91:11–27. <https://doi.org/10.1016/j.oceaneng.2014.08.011>
33. Kadhim MMA, Jawdhari AR, Altaee MJ, Adheem AH (2020) Finite element modelling and parametric analysis of FRP strengthened RC beams under impact load. *J Build Eng* 32:101526. <https://doi.org/10.1016/J.JOBE.2020.101526>
34. Demartinod XX, Wud XG, Xiaod XY (2017) Response of shear-deficient reinforced circular RC columns under lateral impact loading. *Int J Impact Eng* 109:196–213. <https://doi.org/10.1016/j.ijimpeng.2017.06.011>
35. Fujikake K, Li B, Soeun S (2009) Impact response of reinforced concrete beam and its analytical evaluation. *J Struct Eng* 135(8):938–950. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000039](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000039)
36. Plauk G (1982) Concrete structures under impact and impulsive loading
37. Raval R, Dave U (2013) Behavior of GFRP wrapped RC columns of different shapes. *Procedia Eng* 51:240–249. <https://doi.org/10.1016/J.PROENG.2013.01.033>
38. Narule GN, Bambole AN (2018) Axial behavior of CFRP wrapped RC columns of different shapes with constant slenderness ratio. *Struct Eng Mech* 65(6):679–687. <https://doi.org/10.12989/SEM.2018.65.6.679>
39. Wei Y, Xu Y, Wang G, Cheng X, Li G (2022) Influence of the cross-sectional shape and corner radius on the compressive behaviour of concrete columns confined by FRP and stirrups. *Polymers* 14(2):341

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