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Performance Comparison of High Strength Reinforced Concrete Circular and Square Columns Subjected to Flexural Controlled Cyclic Loading

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Abstract

In existing design practices selection of circular or square column shape mostly depends upon architectural needs rather than structural behavior. The behavior of equivalent area (circular and square), high strength reinforced concrete columns is reported to be same under monotonic loading conditions but their behavior under fatigue loading is not well-established. This paper presents the comparison of high strength reinforced concrete circular and square equivalent area columns' performance (load-deflection behavior) under fatigue loading. Columns were casted in four configurations: square and circular shapes and with and without shear stirrups. Experimental results showed that in case of columns without shear stirrups, the square column resisted 38% more loading cycles as compared to circular column while the maximum deflection was 78% more than the circular column. Similarly, in case of columns with shear stirrups, square shaped column resisted 55% more loading cycles with only 5% more maximum deflections as compared to circular column. The results show that the square columns might be considered more ductile as compared to circular columns under the application of cyclic loading conditions like wind forces or seismic forces. Therefore, it might be concluded that square columns should be recommended for highly seismic regions as compared to circular columns with equivalent area.

Keywords: Fatigue Behavior; Circular Columns; Square Columns; Flexural Behavior; Cyclic Loading; High Strength Concrete.

1. Introduction

Reinforced concrete is one of the most widely used construction material around the world. With growing needs, high strength concrete was introduced which could resist considerably more stresses and offered other performance benefits as well [1, 2]. In moment resisting reinforced concrete structures, main RC frame resists and transfers the load to the soil underneath. In this load transfer mechanism RC columns act as the most important components as they provide major resistance against collapse of super structure. The most commonly used cross-sectional shapes of these columns are circular and square/rectangular. The selection of column's shape is usually governed by the architectural requirements and only little consideration is given to the fatigue life performance of each shape. As the axially loaded

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RC members provide major resistance against collapse of super structure, further investigation regarding the fatigue performance of these RC elements is required.

Numerous studies were carried out to investigate the mechanical performance of square and circular columns under different loading conditions like flexure, shear, torsion etc. A detailed study was carried out on the ductility of columns subjected to monotonic flexural loading and it was reported that the ductility of columns is affected by different parameters including the cross-sectional dimensions, slenderness and loading mechanism etc. [3]. A similar study was carried out to investigate the behavior of RC columns subjected to cyclic uniaxial bending. The columns in this study were cantilevered and torsion was also applied to study its effect [4]. Past investigations on the effect of cross-sectional aspect ratio reported that the load-deflection performance of RC columns is dependent on aspect ratio of cross sectional dimensions and becomes insignificant when the ratio reaches 2.0. This research shows that the behavior of column changes with the change in cross-sectional shape if the confinement provided to columns is not adequate under cyclic loading [5-7]. Some investigations were carried out on RC columns with additional confinement provided by FRP and CFRP wraps which show the effect of cross-sectional shape and confinement on the behavior of RC columns subjected to cyclic loading [8-10]. Similar investigations were carried out on the behavior of RC columns subjected to flexural and torsional stresses and the effects of confinement on performance of reinforced columns were reported [11-14].

Furthermore, past studies have reported that the calculations required for flexural capacity of circular RC members are relatively complex as compared to the rectangular or square members [15-17]. According to the Japan Society of Civil Engineers (JSCE) specifications, the capacity of circular column is determined by converting it to an equivalent area square column but the effect of longitudinal reinforcement present on compression side is not considered [18].

From the literature review it can be observed that a lot of research is available on the behavior of reinforced concrete columns subjected to different types of loading and different confinement techniques. However, the performance comparison of the most commonly used column shapes is difficult to be found. Therefore, authors feel a need for comparison of fatigue life performance (under flexural controlled cyclic loading) of high strength concrete square and circular columns with equivalent area of cross section. A similar study was carried out by the authors to compare the load-deflection performance of equivalent area circular and square columns subjected to monotonic flexural and shear controlled loading. It was reported that equivalent area circular and square columns behave in a very similar way under single cycle flexural and shear controlled loading. The deflection and load bearing capacity of both shapes was comparable. The comparison was carried out for different reinforcement patterns [19-21].

In this study authors have considered same equivalent area circular and square columns and subjected them to flexural controlled high cycle fatigue loading. Furthermore, to enhance the investigation two types of specimens were investigated, with shear stirrups and without shear stirrups. The specimens without shear stirrups were investigated to study the effect of cross-sectional shape and reinforcement location on the load-deflection behavior of columns. The research article has been formulated using three major sections i.e., the details of speciemns and experimental setup has been explained in experimental approach, the results and related discussion has been provided under results and discussions and finally the conclusions have been presented.

2. Experimental Approach

2.1. Materials and Concrete Mix

The mix proportion used to cast circular and square columns have been given in Table 1. The 28 days compressive strength of concrete was 75 MPa. Grade 60 steel rebars were used to reinforce the concrete specimen. Well graded fine and coarse aggregates were used after proper washing (Figure 1).

Table 1. Concrete mix proportions

Constituent Name	Proportion per m^3 of concrete (kg/m^3)
Cement	359
Sand	932
Aggregate	1009
Water	176
Admixture	3.6
W/C	0.48

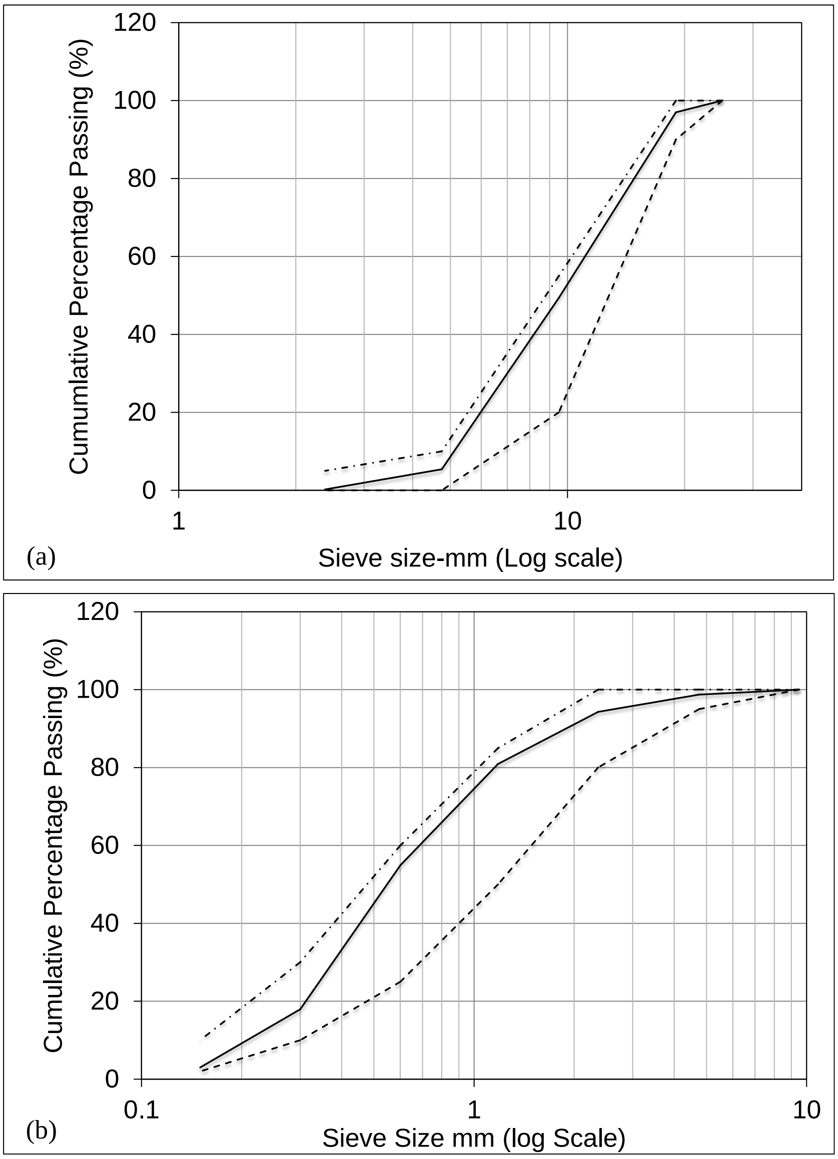

Figure 1. Gradation curves of coarse and fine aggregates, (a) Gradation Curve of Coarse; (b) Gradation Curve of Fine Aggregates

2.2. Specimens Casted

In this study equivalent area circular and square columns were casted to study their load-deflection behavior under flexural high cycle fatigue loading. The diameter of circular column was 150mm while the square column's dimension was 133mm which would give equal area (Cross sectional area ≈ 17680 mm^2). Both columns were 1600mm long reinforced with 12 – Grade 60 rebars of 6mm diameter (Figure 2). Each of these columns was casted in two variants, with shear stirrups and without shear stirrups. These variants were selected to properly investigate the effect of shape and effect of confinement provided to reinforced concrete columns.

For square columns special PVC molds were prepared to give them desired dimension (calculated according to the equivalent area of circular columns). Paper pipes were used to cast circular columns as shown in Figure 3.

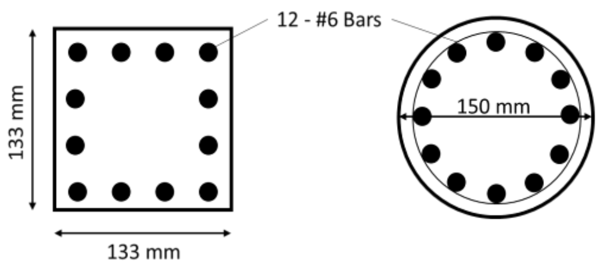

Figure 2. Cross-Sectional Details of Circular and Square Columns

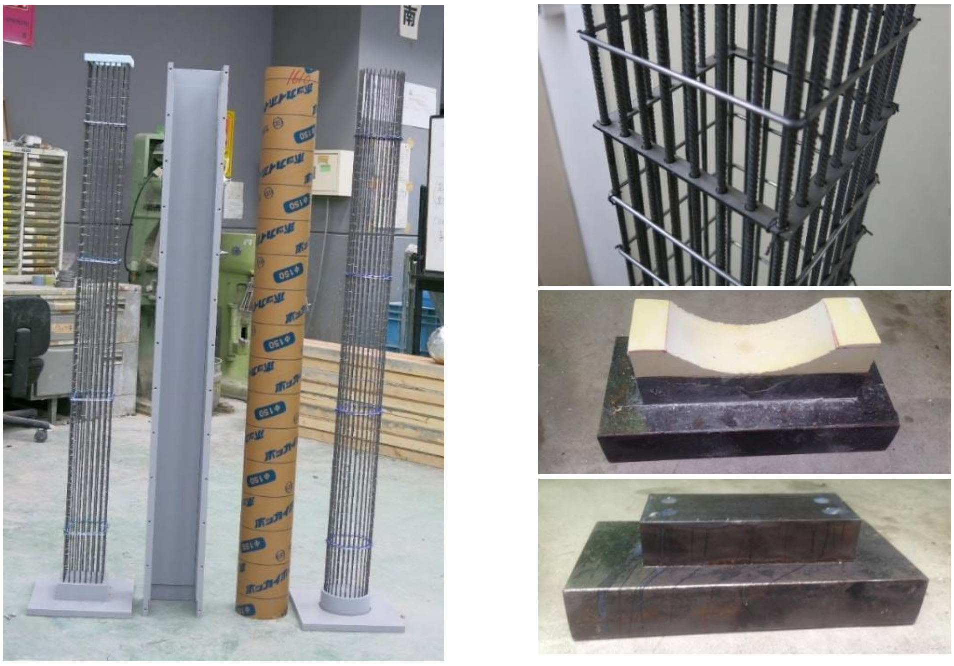

Figure 3. Column molds and reinforcement arrangement

2.3. Test Setup

HSC reinforced circular and square columns were tested under cyclic flexural load to compare their performance. These columns were subjected to four-point flexural loading test. Universal testing machine was used to apply cyclic loading. The cyclic load was given increments after specific intervals. Test was started with 10kN initial load taken up to 40kN and applied for first 25 cycles. After each set of 25 cycles, the load was increased by 1kN (Figure 4). Shear-span was varied to control the failure mode (bending and shear failure modes were investigated) as shown in Figure 4. In this study the distance between supports and loading points was calculated to give flexural failure corresponding to monotonic loading conditions. These values were calculated corresponding to the single cycle loading conditions as reported by Mohammed et al. (2018) [20]. Other parameters including the column dimension, steel reinforcement etc. were also kept same. The overall research program has been shown in form of a flow chart in Figure 5.

To maintain uniformity among columns of different shapes, special support system was devised to provide same contact area to square and circular shaped columns. The contact area was kept equal to 5mm wide by 1/4th of circumference/perimeter of column (Figure 6). LVDTs were fixed on loading points and mid-point of the columns to study load-deflection behavior. Load cell was used to record the total load applied by UTM on the columns.

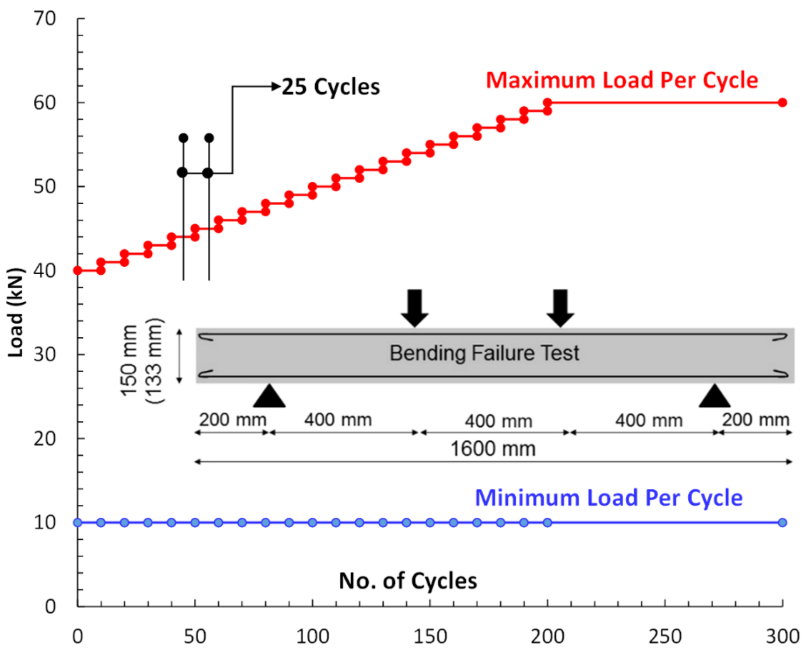

Figure 4. Cyclic/Fatigue loading scheme and Schematic diagram of flexural controlled four point loading test

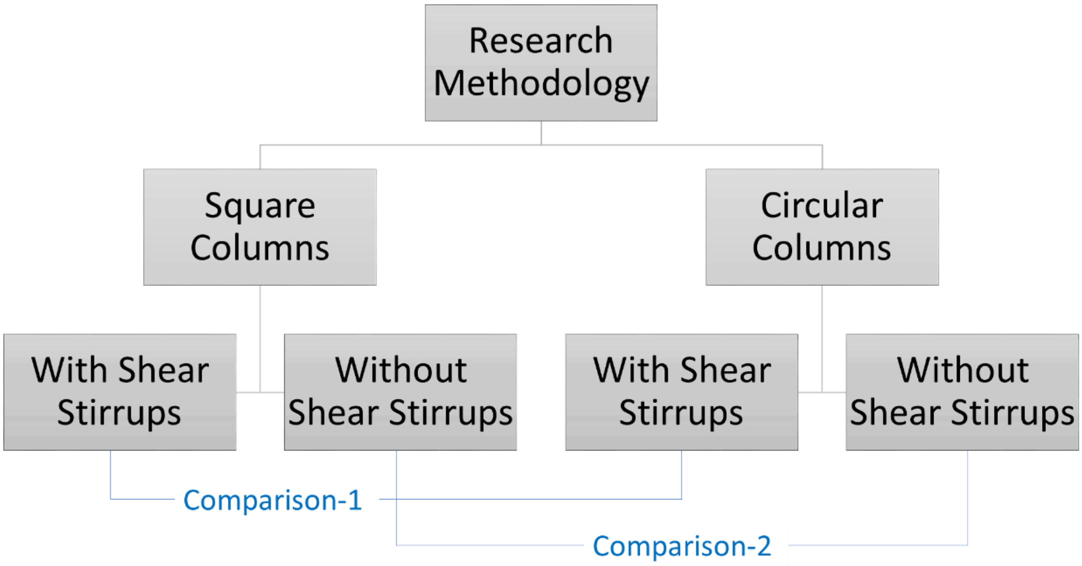

Figure 5. Flow chart of Research methodology

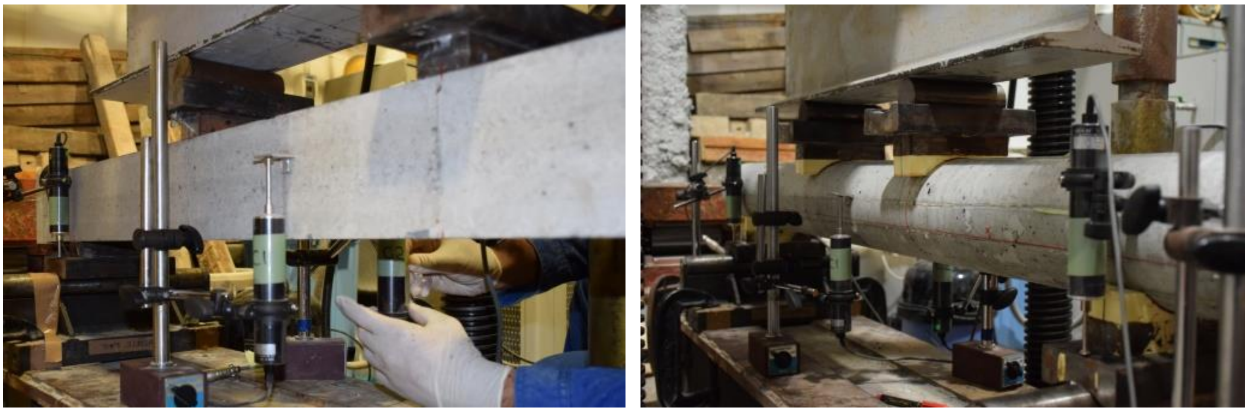

Figure 6. Experimental set up of test specimens subjected to flexure

3. Results and Discussions

Circular and square columns were tested under flexural conditions as described earlier. The load was applied in intervals of 1kN and applied for 25 loading cycles. Load cell was used to record the total load applied by UTM while LVDTs were used to record the deflections at mid-point and load points. Two LVDTs were installed at these locations on each side of the column. The load-deflection behavior of circular and square columns corresponding to mid-point deflections and loading point deflections have been presented in this paper, but detailed discussion has been focused on mid-point deflections. Several parameters including no. of loading cycles, maximum deflection and maximum load have been discussed in this article.

3.1. Behavior of Square Column without Shear Stirrups

The columns with square cross-sectional shape were tested under flexural conditions and their load-deflection behavior has been shown in Figure 7. The deflection shown in this figure is the average of two LVDTs fixed on each side of the column. It was observed that the square column without shear stirrups could resist 350 loading cycles before final failure. The average mid-point deflection was 72mm while the deflection at the loading point was observed to be 56mm. The maximum load resisted by this column before failure was 55.4 kN. At initial loading cycles, the stiffness degradation in columns was very little. Under this type of loading conditions, the deflections after each cycle were not growing considerably. Crack generation was gradual with numerous flexural cracks appearing in the central 1/3rd portion of the column in the earlier stages of fatigue loading. Cracks started appearing outside the central portion at later stages of loading. Cracks outside the central portion were not as wide as the cracks inside the central portion of column. The final failure of column was in flexure with no wide-open shear cracks. The expected final failure was also flexural failure due to the distance kept between loading and support points. The final crack pattern has been shown in Figure 8.

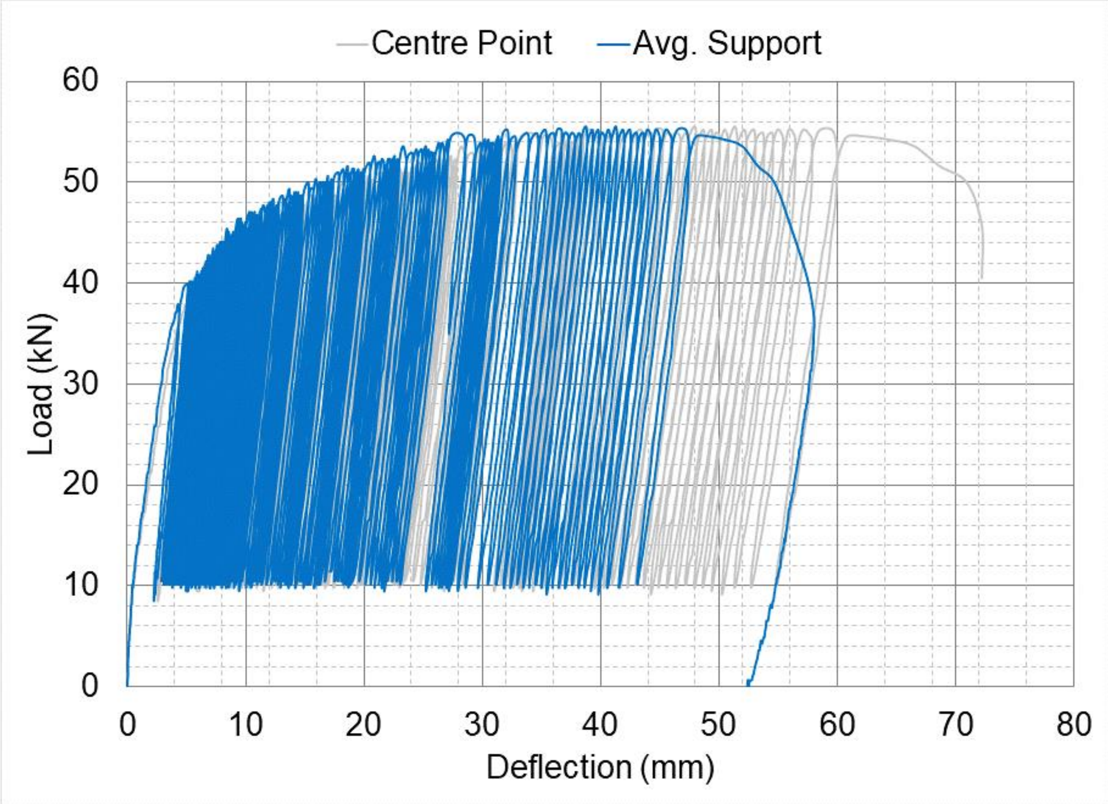

Figure 7. Load-Deflection Behavior of Square Column subjected to Fatigue Loading in Flexural Conditions without Shear Stirrups

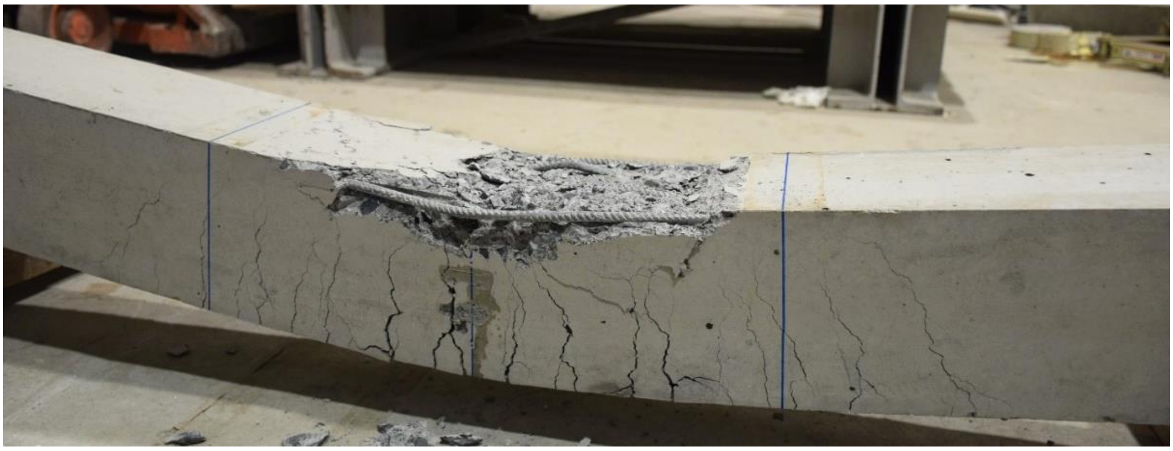

Figure 8. Failure Pattern of Square Column subjected to Fatigue Loading in Flexural Conditions without Shear Stirrups

3.2. Behavior of Square Column with Shear Stirrups

After testing the column under fatigue loading without shear stirrups, columns were tested with shear stirrups. The columns showed relatively more ductility due to the extra confinement added by the shear stirrups. The load to deflection behavior of the column has been shown in Figure 9 while the failure mechanism is shown in Figure 10. The total number of cycles observed before failure were 423 with maximum deflection of 76.8mm at the center of the column and 68mm at the loading point. The maximum load carried by the column was 57 kN. The maximum load taken by the column was comparable to the case without shear stirrups primarily because the final failure is controlled by flexural conditions. But at the same time the maximum deflection showed by this type of column was greater than the column without shear stirrups. The number of cycles resisted before failure is also large with maximum cycles confined within 20mm deflection range due to better confinement (due to shear stirrups) as shown in Figure 9. The crack pattern was also similar to the columns without shear stirrups with most of the cracks appearing in flexural zone.

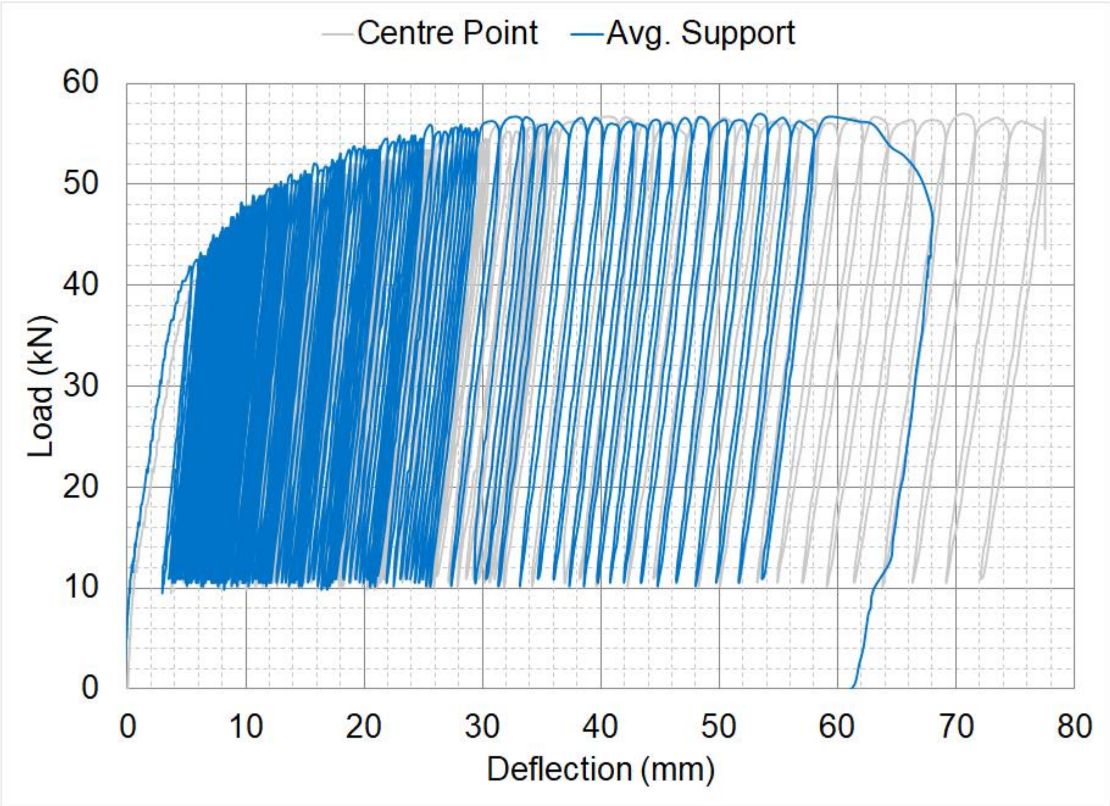

Figure 9. Load-Deflection Behavior of Square Column Subjected to Fatigue Loading in Flexural Conditions with Shear Stirrups

Figure 10. Failure Pattern of Square Column Subjected to Fatigue Loading in Flexural Conditions with Shear Stirrups

3.3. Behavior of Circular Column without Shear Stirrups

Similar to Square columns, circular columns without shear reinforcement were subjected to fatigue loading under flexural conditions. High cycle fatigue load was applied with 1kN increment after every 25 cycles, the behavior of column was logged in form of load vs. deflection curve as shown in Figure 11. The deflection was measured at the mid-point and at the loading points. The average values of two LVDTs have been plotted in the load-deflection curve. The total numbers of cycles taken by the circular column before failure were 254 with maximum deflection of 35mm at the loading points and 40.5mm at the center of the column. The maximum load taken by the column before failure was 51.9 kN. During the initial loading cycles the stiffness degradation of circular column was small as compared to the square column but at the later stages (beyond 7mm deflection range) the stiffness degradation started increasing. This affected the number of cycles and the maximum deflection exhibited by the circular column before failure but the maximum load resisted by the column was close to the square column. 7% reduction was observed in the experimental load carrying capacity circular columns (as compared to the equivalent area square columns). The crack pattern at the failure is shown in Figure 12. Flexural cracks appeared in the central 1/3rd portion of the circular column (between the two loading points). The number of cracks was not large and at the same time the crack width for each of these cracks observed during testing, was larger as compared to the square columns. The final failure of circular column was in flexure with no wide-open shear cracks. The expected final failure was also flexural failure due to the distance kept between loading and support points.

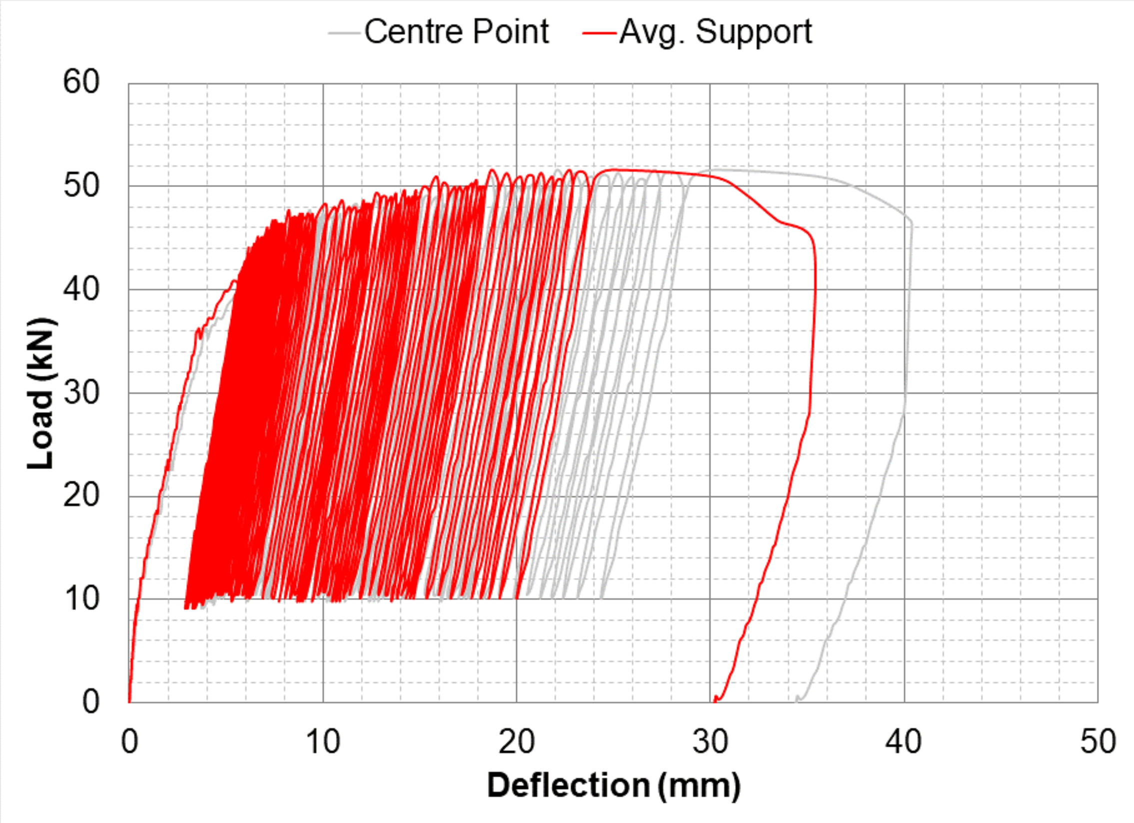

Figure 11. Load-Deflection Behavior of Circular Column subjected to Fatigue Loading in Flexural Conditions without Shear Stirrups

Figure 12. Failure Pattern of Circular Column Subjected to Fatigue Loading in Flexural Conditions without Shear Stirrups

3.4. Behavior of Circular Columns with Shear Stirrups

After the circular columns without shear stirrups, circular columns with shear stirrups were also subjected to fatigue loading. The circular columns showed relatively more ductility due to the extra confinement added by the shear stirrups. The load to deflection behavior of the column has been shown in Figure 13 while the failure mechanism is shown in Figure 14. The total number of cycles observed before failure were 274 with maximum deflection of 56mm at the loading point and 73.5mm at the center of the column. The maximum load carried by the column was 53 kN. The maximum load was close to the case without shear stirrups. This similarity is due to the flexural controlled conditions maintained by keeping the distance between loading points and supports accordingly. The maximum deflection at the center point was 73.5 mm which is quite large as compared to the previous case where the deflection was 40.5 mm. Although the ultimate load is close to the case without shear stirrups (4% increase), the increase in the number of cycles and maximum deflection exhibited by the column shows the increased ductility due to shear reinforcement. This increase in ductility is the prime requirement especially for the structures prone to earthquakes.

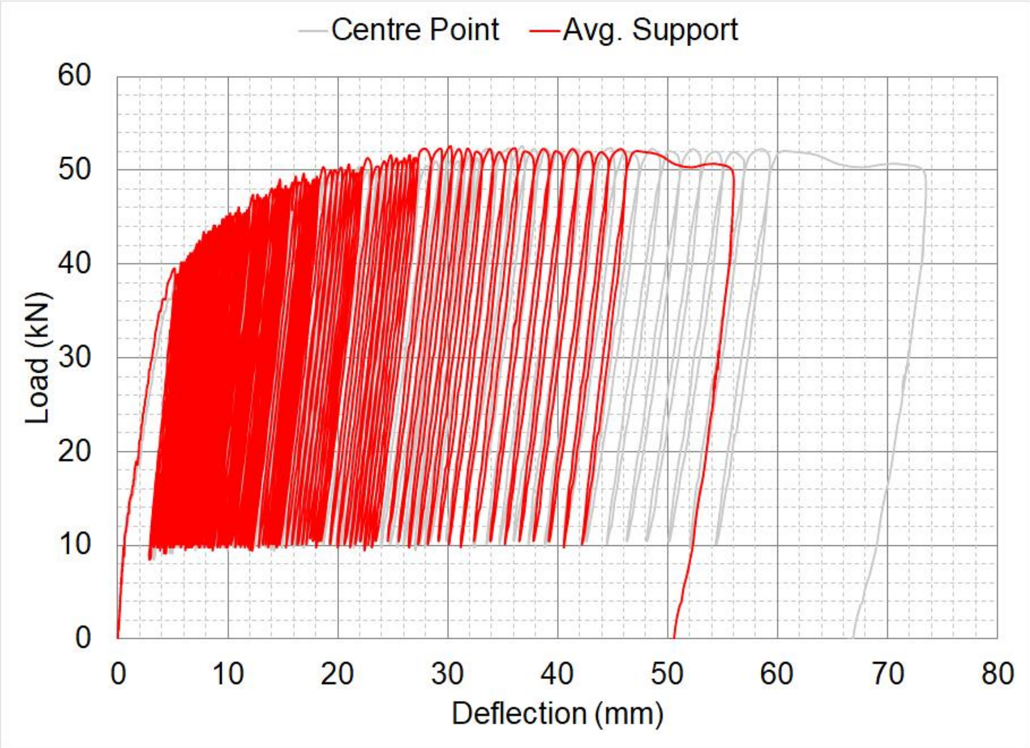

Figure 13. Load-Deflection Behavior of Circular Column Subjected to Fatigue Loading in Flexural Conditions with Shear Stirrups

Figure 14. Failure Pattern of Circular Column Subjected to Fatigue Loading in Flexural Conditions with Shear Stirrups

3.5. Performance Comparison of Square and Circular Columns without Shear Stirrups

Initially the behavior of circular and square columns is compared for the cases without shear stirrups. The number of loading cycles and maximum load resisted by each type of column have been considered as the comparison basis. Figure 15 shows the comparison of load-deflection behavior of square and circular columns while Figures 16 to 18 shows a comparison between loading cycles, maximum deflection and maximum load resisted by square and circular columns. The square column failed after 350 loading cycles with a maximum deflection of 72 mm at the center point of the column while the circular column failed after 254 loading cycles and a maximum deflection of 40.5 mm. The maximum load resisted by square and circular columns was 55.4 and 51.9 kN respectively. Although the maximum load resisted by each type is close, but the maximum deflection shown before failure and the number of loading cycles are different. Square column without shear stirrups resisted 40% more loading cycles and the maximum deflection observed in case of square column was 78% more as compared to circular column without shear stirrups. One major reason for this type of behavior is the shape effect. In case of square columns, the flat surface on the edge presents relatively larger area of concrete to resist the applied stresses at the instance these are applied. In case of circular columns the concrete area and the steel reinforcement is subjected to the applied stresses gradually as the stresses on the edge are larger than the stresses near the neutral axis. This gives an idea of square columns being a better choice under flexural conditions as compared to the circular columns. But this comparison is for the cases where square and circular columns were tested without any additional confinement being contributed by shear stirrups. The presence of shear stirrups may increase the ductility and enhance the performance of columns under fatigue loading. Figure 19 shows the failure pattern of square and circular columns. The crack pattern of two types of columns show that the square column developed more number of cracks as compared to circular column before failure. This is the primary reason for square column being able to withstand more number of cycles as compared to circular column and exhibit more ductility in terms of maximum deflection before failure. This comparison brings us to a conclusion that square columns behave in more ductile way as compared to circular columns when there is no confinement provided by the shear stirrups.

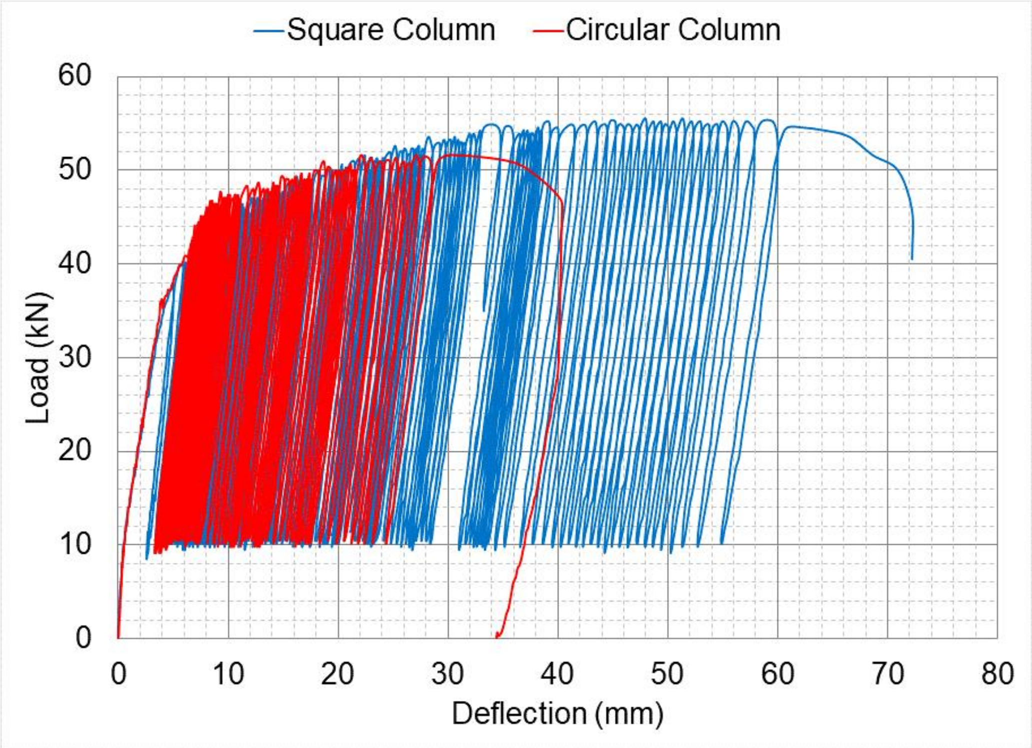

Figure 15. Load-Deflection comparison of square and circular columns Subjected to flexure conditions without shear stirrups

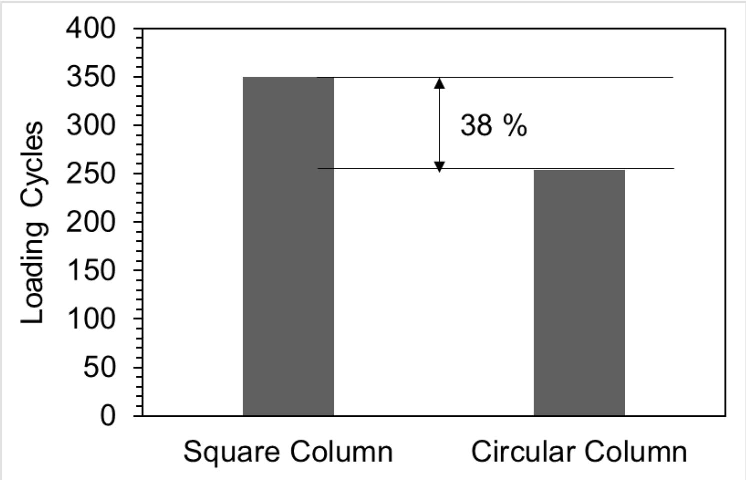

Figure 16. Loading cycles resisted by square and circular RC columns without shear stirrups

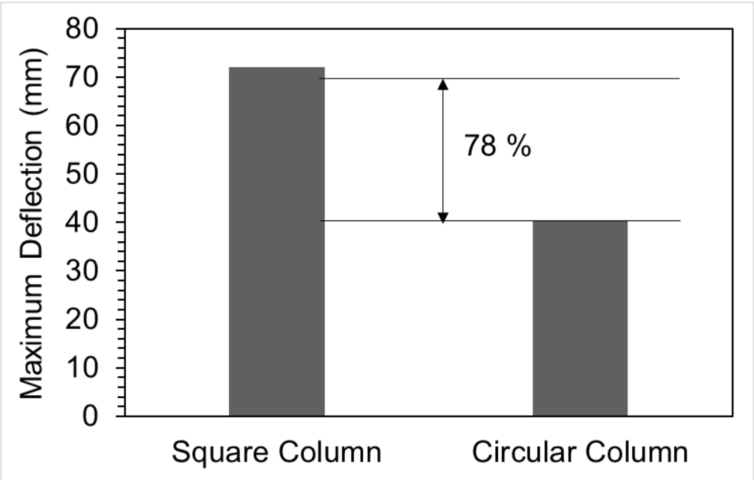

Figure 17. Maximum deflections shown by square and circular RC columns without shear stirrups

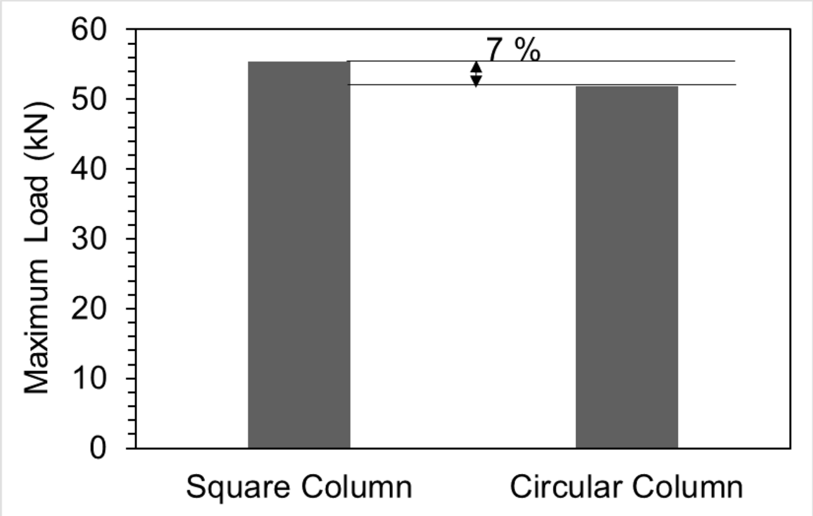

Figure 18. Maximum loads resisted by square and circular RC columns without shear stirrups

Figure 19. Failure pattern comparison of square and circular columns under flexure conditions without shear stirrups

3.6. Performance Comparison of Square and Circular Columns with Shear Stirrups

Now the behavior of circular and square columns is compared for the cases with shear stirrups. Figure 20 shows the comparison of load-deflection behavior of square and circular columns while Figures 21 to 23 shows a comparison between loading cycles, maximum deflection and maximum load exhibited by square and circular columns respectively. The square column failed after 423 loading cycles with a maximum deflection of 76.8 mm at the center point of the column while the circular column failed after 274 loading cycles and a maximum deflection of 73.5 mm. The maximum load taken by square and circular columns was 56.7 and 53 kN respectively. As compared to the columns without shear stirrups, the difference between loading cycles and maximum deflection exhibited by columns with shear stirrups grew even bigger. Square column with shear stirrups took around 55% more loading cycles but the maximum deflection observed in case of square column was around 38% more as compared to circular column without shear stirrups. This change in behavior can be explained by the change in shape. In case of square columns the area of concrete and steel reinforcement near the surface is more as compared to circular columns. The applied stresses vary throughout the cross section of flexural members. Usually, the values are maximum near the surface/edge and reduce to minimum near the neutral axis. Hence, there is more area of concrete and steel available to resist the applied stresses near the surface which might delay the initiation of cracks. These results show that the comparison situation between square and circular columns gets complex when both are reinforced with shear stirrups. The percentage increase in loading cycles resisted by square column with shear stirrups grows from 38 to 55% as compared to the respective circular column. However, the percentage increase in the maximum deflection of square column with shear stirrups as compared to the circular column was only 5% as compared to the case without shear stirrups where this value was 78%. The difference between maximum loads resisted by each type was observed to be 8% which is similar to the previous case (without shear stirrups). Figure 24 shows the failure pattern of square and circular columns with shear stirrups. The crack pattern of both types of columns is quite similar. Both square and circular columns developed nearly similar number of cracks. The no of loading cycles bring us to the conclusion that square columns are relatively more ductile as compared to circular columns even in the presence of shear stirrups.

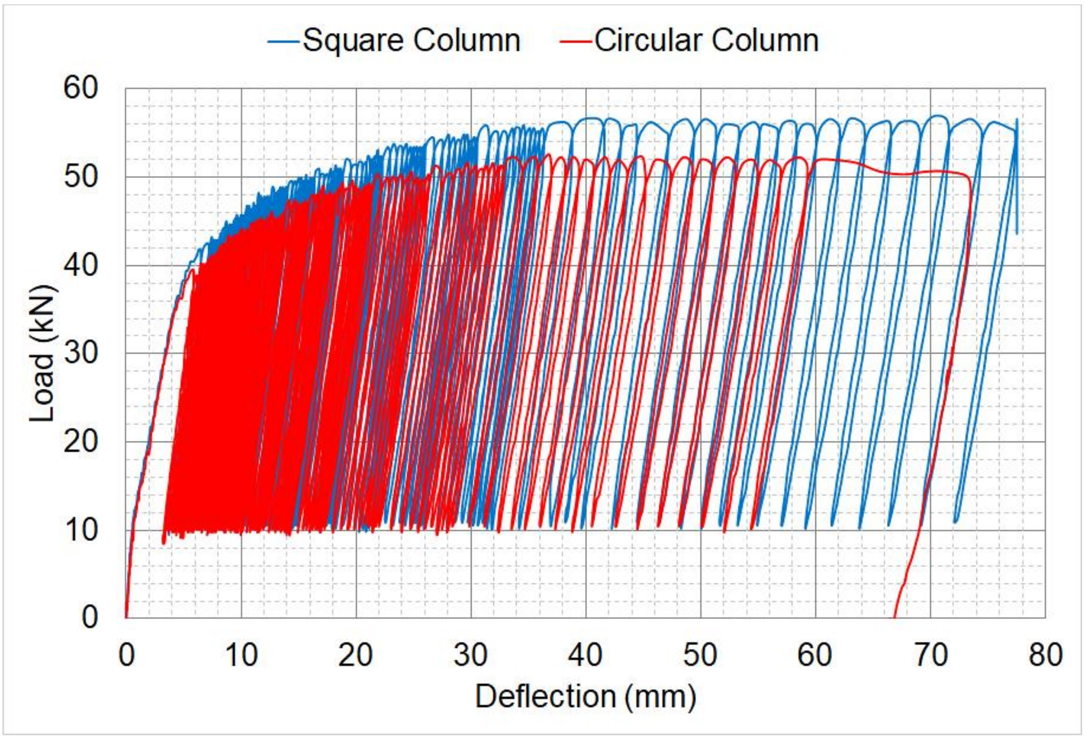

Figure 20. Load-Deflection comparison of square and circular columns Subjected to flexure conditions with shear stirrups

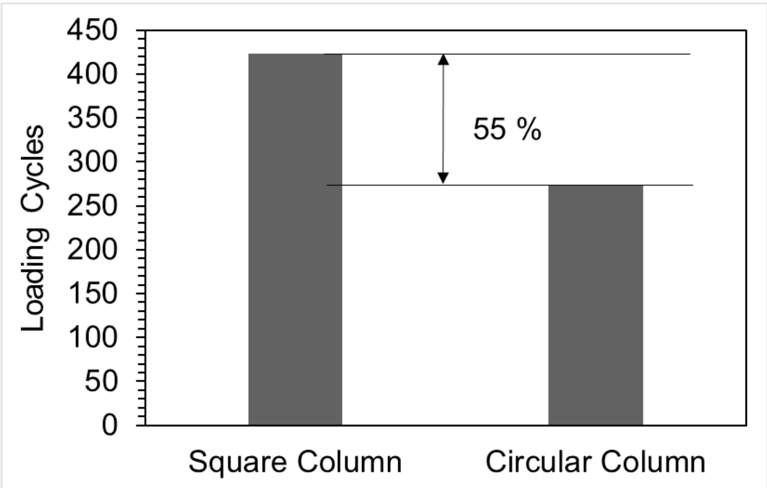

Figure 21. Loading cycles resisted by square and circular RC columns with shear stirrups

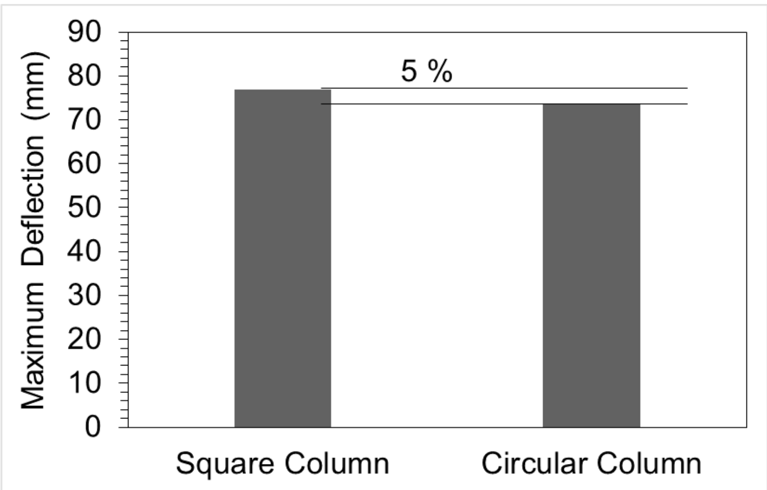

Figure 22. Maximum deflections shown by square and circular RC columns with shear stirrups

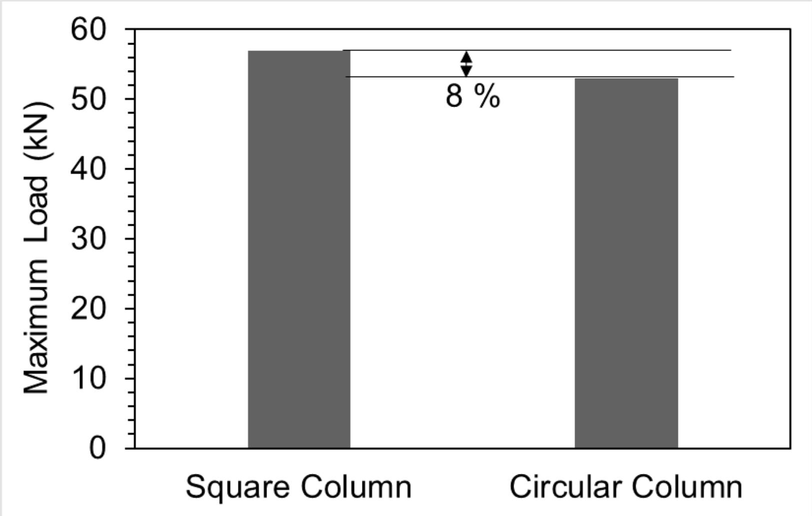

Figure 23. Maximum loads resisted by square and circular RC columns with shear stirrups

Figure 24. Failure pattern comparison of square and circular columns Subjected to flexure conditions with shear stirrups

4. Conclusion

Authors feel a need to study the comparison of flexural behavior of circular and square columns with equal area of concrete and steel. For the above purpose, equivalent area Square and circular columns were tested under flexural-controlled fatigue loading conditions. The specimens were subjected to four-point loading test where the shear span was controlled to avoid shear failure. In order to investigate the effect of shape on the performance of columns, all columns were tested in two configurations; with shear stirrups and without shear stirrups. The performance comparison has been drawn using total number of cycles, maximum deflections and ultimate load resisted by each column type. First comparison was drawn between square and circular columns without shear stirrups. The comparison shows that square columns without shear stirrups are more ductile as compared to circular columns without shear stirrups under flexural-controlled conditions. The reason for this conclusion is 38% more loading cycles resisted by square column as compared to circular column while the maximum deflection in square column was also 78% more than the circular column. The maximum load resisted by square column was 7% more than the circular column. The second case was with shear stirrups and this comparison shows similar results where square columns prove to be more ductile under flexural-controlled fatigue loading conditions. In this case the square column resisted 55% more loading cycles as compared to circular column while the maximum deflection shown by square column was 5% more than the circular column. In this case, the maximum load resisted by square column was 8% more than the circular column. These results are applicable to the case where equivalent area square and circular columns are being considered.

This comparison shows that square columns might be considered more ductile as compared to the circular columns due to more capacity of resisting loading cycles. However, the ultimate load resisted by each type is not very different. Furthermore, circular columns presented a stiffer behavior exhibiting lesser deflections. Based on the results it may be concluded that square columns should be preferred in the regions subjected to frequent seismic activities or high wind forces. However, circular columns might be preferred when there is a need to keep deflections under certain limits.

5. Declarations

5.1. Author Contributions

The basic theme of the research was discussed and decided by all three authors. The manuscript was written by Ali Ahmed and Ahmed Mohammed Youssef Mohammed while the experimental research work was carried out by Ali Ahmed and Ahmed Mohammed Youssef Mohammed, the results and discussions and conclusion section was completed by all three authors.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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