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SHEAR CAPACITY EVALUATION OF REINFORCED CONCRETE BEAMS: FINITE ELEMENT SIMULATION

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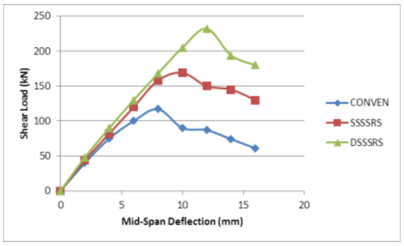
Graphical abstract



Abstract

The shear performance of reinforced concrete beams with rectangle cross-section and two different continuous rectangular spiral shear reinforcement under monotonous loading is numerically evaluated. Further, the behaviour of two continuous shear reinforcement systems named, "Single Square Spring Shear Resistance System" (SSSSRS) and "Double Square Spring Shear Resistance System" (DSSSRS) as transverse reinforcements are compared with conventional discontinuous system "Stirrups". The finite element study includes three (3) beams. The results clearly show that the application of continuous shear reinforcement system delivered improved shear behaviour and enhanced bearing capacity in beams. Beams with Single Square Spring Shear Resistance System (SSSSRS) and Double Square Spring Shear Resistance System (DSSSRS) exhibited 14.4% and 19.8% increased shear performance in comparison with conventional control beam. It was concluded that under the same deflection higher forces was achieved for "Single Square Spring Shear Resistance System" (SSSSRS) and "Double Square Spring Shear Resistance System" (DSSSRS) compared to control specimens.

Keywords: Reinforced concrete beam, continuous shear system, single square spring shear resistance system, double square spring shear resistance system

1.0 INTRODUCTION

Basically using the continuous spiral reinforcement in Reinforced Concrete (RC) elements with cyclic cross-section can significantly improve the strength and the ductility of the concrete and hereafter the total seismic performance and capacity of the structural element [1–5]. Recently, the application of continuous spiral reinforcement has been extended in RC elements with rectangular cross-sections. Application extension of rectangular continuous spiral reinforcement in elements with rectangular cross-sections is an effective technology that is estimated it can enhance the capacity and the performance of the these RC members [7].

It is highlighted that spiral reinforcement extends like an accordion and thus it can easily and quickly be tied into place. This kind of installation clearly reduces labour cost in comparison with the installation of the single closed stirrups. Also, conventional single closed stirrup installation demands the formation of two end hooks for anchorage. The length of these two hooks for each closed stirrup is an extra amount of the material that increases steel weigh and finally will affect the total cost. This issue is not required in spiral reinforcement installation and as a result, the total cost is obviously reduced. This benefit becomes significant in the cases of RC columns where multiple stirrups per cross-section are required to be placed and further to the extra hooks, steel overlaps of stirrups are also unavoidable. Therefore, reduction of the cost due to the nature of the application of the new product is yielded from the use of continuous spiral reinforcement and in some cases it may be considered as an important benefit.

For the first time, using the rectangular spiral reinforcement in shear-critical RC beams with rectangular cross-section have been reported by Karayannis *et al*. [9], whereas Yang *et al*. [10] tested the shear performance of concrete T-beams that have been reinforced using spiral-type wire rope as internal shear reinforcement. Considering the behaviour of shear-critical members, it is stressed that the shear failure of a RC beam is characterised by the inclination of the diagonal cracking. It has been experimentally verified that the amount of the steel stirrups along with the amount of the main tension reinforcement and the span-to-depth ratio control the inclined shear cracking [11]. The use of steel fibres as the only shear reinforcement in lieu of stirrups in concrete beams under predominant shear and torsion proved to be a promising alternative solution under specific situations [12, 13]. The application of steel spiral reinforcement though seems to be a more effective technique. However, it is stressed that common continuous spiral reinforcement comprises two vertical links with opposite inclination and therefore, only one of these links has the right inclination to resist against the applied shear.

As it can be concluded from the review of literature most of the experimental research has been conducted to investigate the behaviour of spirally reinforced circular RC elements. So far, the published work on the use of rectangular spiral reinforcement as shear reinforcement in RC elements with rectangular cross-section is very limited.

In this work, the behaviour of RC beams with rectangular cross-section and rectangular spiral reinforcement as transverse reinforcement under monotonous loading is numerically evaluated. Further, an advanced rectangular spiral reinforcement that consists of two continuous links is also presented here as shear reinforcement for the beams. The contribution of the simulated rectangular spiral reinforcement to the overall performance of the beams is also reported and commented. The design provisions of the Eurocode (EC2, EC8-04) [14-19] have been used in order to estimate the ultimate shear strength of the tested beams. Based on the observed test results, a first approach to estimate the contribution of the spiral reinforcement on the ultimate shear capacity is also presented here.

2.0 ANALYTICAL PREDICTIONS

The design of reinforced concrete beams is primarily based on flexural and shear strength. Once the design of a reinforced concrete member is preferred, flexure would be the first item to be considered which eventually leads to the determination of the section size and arrangement of reinforcement to provide the required resistance for moments. The shear design must be in a way so that the shear strength for every structural member exceeds the flexural strength. The mechanism of shear failure is a function of the cross-sectional dimensions, the shear reinforcement properties of the member and type of loading. Normally, formation of the inclined shear cracks initiates at the middle height of the beam near supports at almost 45 degree and extends towards the compression zone. Resistance against the shear forces near supports is provided through application of anchored reinforcement that intersects these diagonal cracks. One great advantage of the rectangular spiral reinforcement system would be its angle that intersects the diagonal shear cracks (Figure 1). The shear design of structural members is conducted using the following equation (ACI 318-02):

$$\varphi V_n \geq V_u \qquad (1)$$

where,

V_u= the factored shear force at the section
Φ = strength reduction factor (0.85 for shear)
V_n= nominal shear strength computed by:

$$V_n = V_c + V_s \qquad (2)$$

where,

V_c= nominal shear strength provided by concrete
V_s= nominal shear strength provided by shear reinforcement for inclined stirrups computed by:

$$V_s = A_v \, f_{yd} \, (\sin(\alpha+\cos(\alpha))/S \qquad (3)$$

where,

A_v = total cross sectional area of web reinforcement within a distance S, for single loop stirrups, A_v= $2A_s$.
A_s= cross sectional area of the stirrup bar (mm^2).
S = center to center spacing of shear reinforcement in a direction parallel to the longitudinal reinforcement (mm).
F_y = yield strength of web reinforcement steel.

It can be inferred from the mentioned equations that the shear resistance could be improved by the angle of shear reinforcement up to 1.41 times once the angle is 45°. Moreover, close installation of stirrups near the high-shear regions in conventional design would lead to congestion near the supports of the reinforced concrete beams and consequently increased time and costs. This problem could be eliminated by using rectangular spiral reinforcement which leads to improved flow of concrete within the member when it is delivered to the site by a truck mixer.

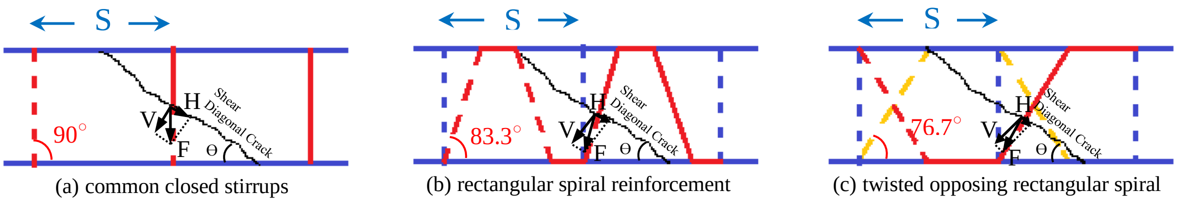


Figure 1 Contribution of the spiral reinforcement on the shear capacity

3.0 NUMERICAL STUDY PROCEDURE

To perform the FEA phase of the study, the FE software ANSYS was used to appropriately simulate the nonlinear behaviour of beams. Three dimensional (3D) FEA was preferred to two dimensional (2D) ones as a result of its higher accuracy. Three techniques exist in modelling the steel reinforcement in the numerical study [6, 8] which as listed as: i) discrete modelling, ii) embedded modelling and iii) smeared modelling (Figure 2). In this study, discrete modelling was used to model the steel bars. To efficiently describe the constitutive behaviour of the reinforcements, the isotropic strain hardening of von Mises yield criterion along with an associated flow rule were applied. The ANSYS options of "separate link 180 elements" were used to model the bars. The reinforcement modelling for all three specimens is shown in Figure 3.

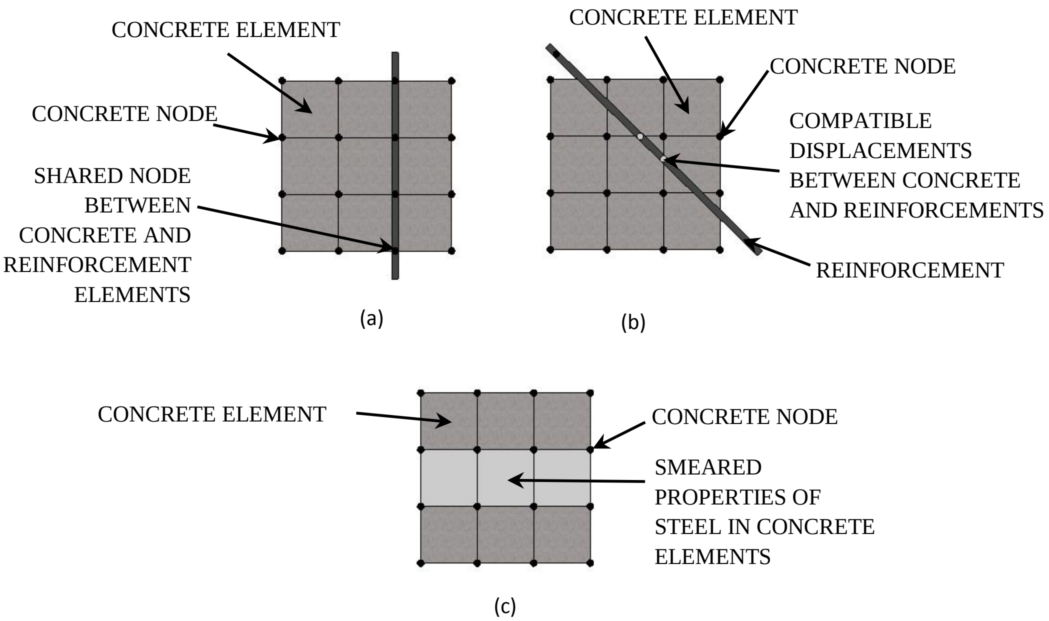


Figure 2 Reinforcement modelling techniques: (a) discrete, (a) embedded, (c) smeared [8]

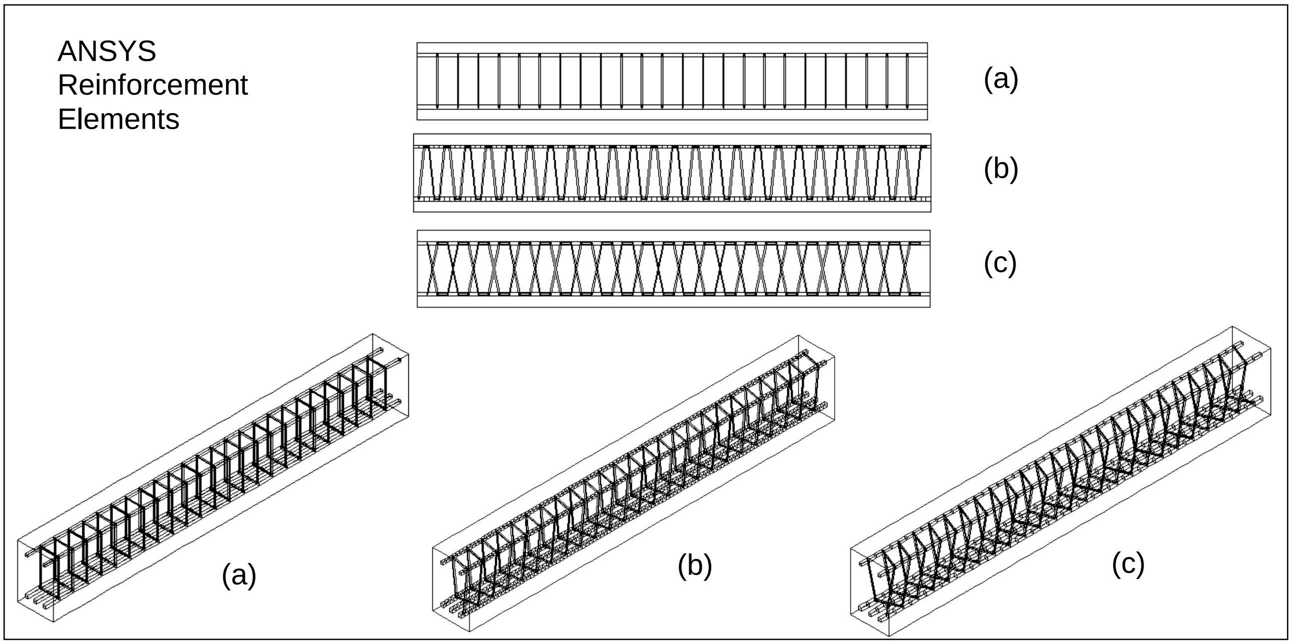


Figure 3 Definition of reinforcement bars with "Link180 Element" in ANSYS (a) CONVEN, (b) SSSSRS, (c) DSSSRS

To appropriately model the concrete behaviour, the "Solid65" element was used along with application of linear isotropic and multi-linear isotropic material properties. Therefore, the von Mises failure criterion with the multi- linear isotropic material was used to properly define the concrete failure. The concrete specimens modelled with ANSYS are shown in Figure 4. Figure 5 and 6 are illustrated material mechanical properties for concrete and steel reinforcement used in finite element simulation.

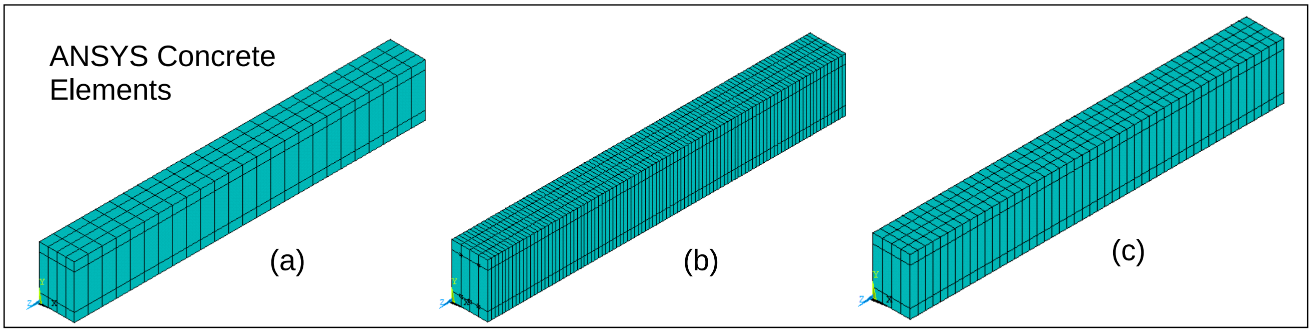


Figure 4 Concrete element modelling with ANSYS using the element "Solid 65" for (a) CONVEN, (b) SSSSRS, (c) DSSSRS

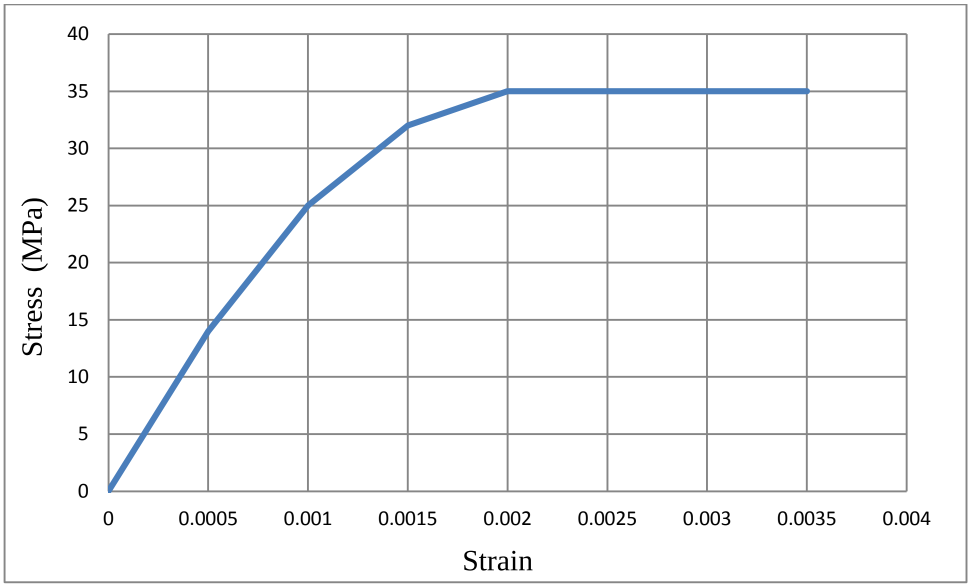


Figure 5 Simplified stress-strain curve for concrete used in finite element model

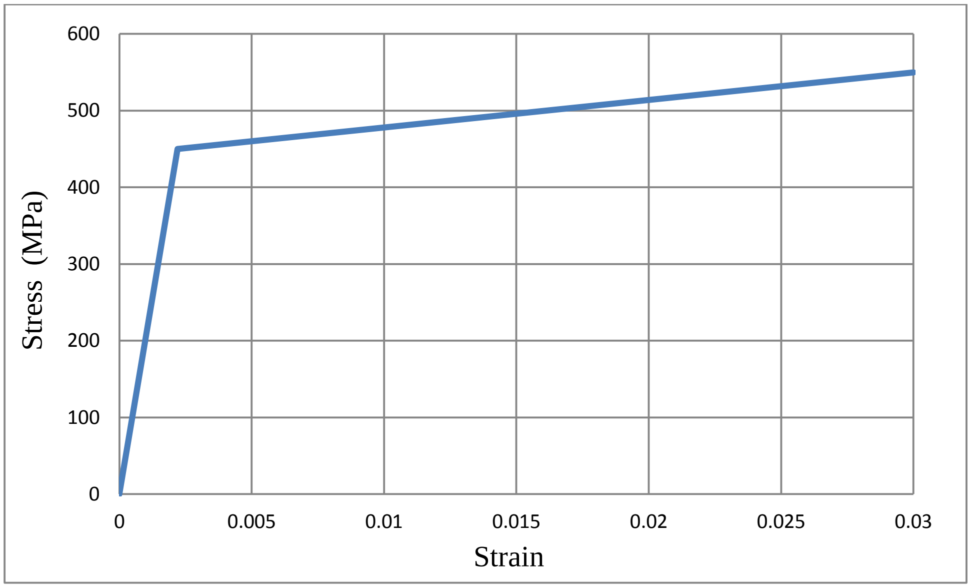


Figure 6 Stress-strain curve for steel reinforcement used in finite element model

4.0 RESULTS AND DISCUSSIONS

All simulated specimens exhibited pure shear response. Based on the amount of the provided longitudinal reinforcement, the cross-sectional dimensions, the concrete compressive strength and the steel yield strength of the beams, the calculated flexural yield capacity is predicted for the beams of "Single Square Spring Shear Resistance System" (SSSSRS), "Double Square Spring Shear Resistance System" (DSSSRS) and the control specimen CONVEN with 2φ14 top and 3φ18 bottom bars and cross-section of 200X300mm. These load values have not been exceeded during the running simulations since the ultimate shear capacity of the tested specimens was expected and proved to be much lower than their flexural strength at yield. Finite element study results in terms of the stress intensity is presented in Figure 7 for all beam specimens.

The behaviour of the beams of SSSSRS and DSSSRS along with the control specimens is presented in Figure 8, in terms of numerical curves of shear load versus mid-span deflections. Test results indicate that the influence of the rectangular spiral reinforcement on the shear capacity of the beams is significant. The "Single Square Spring Shear Resistance System" (SSSSRS) demonstrated higher shear strength values than the corresponding specimens with common closed stirrups (CONVEN). Further, the specimens with advanced rectangular spiral "Double Square Spring

Shear Resistance System" (DSSSRS) exhibited considerably higher shear capacity and improved overall performance with respect to the corresponding specimens with stirrups (CONVEN). The maximum shear loads of all specimens are showed in Figure 9. Beam specimens reinforcement details and Finite Element Simulation results for all specimens are presented in Table 1 and 2 respectively.

Table 1 Beam specimens reinforcement details

Specimens	Main Bars, Top	Main Bars, Bottom	Specimen Dimensions (mm)	Shear Reinforcement
CONVEN	2φ14	3φ18	300X400X2000	Conventional Stirrups
SSSSRS	2φ14	3φ18	300X400X2000	Single Square Spring Shear Resistance System
DSSSRS	2φ14	3φ18	300X400X2000	Double Square Spring Shear Resistance System

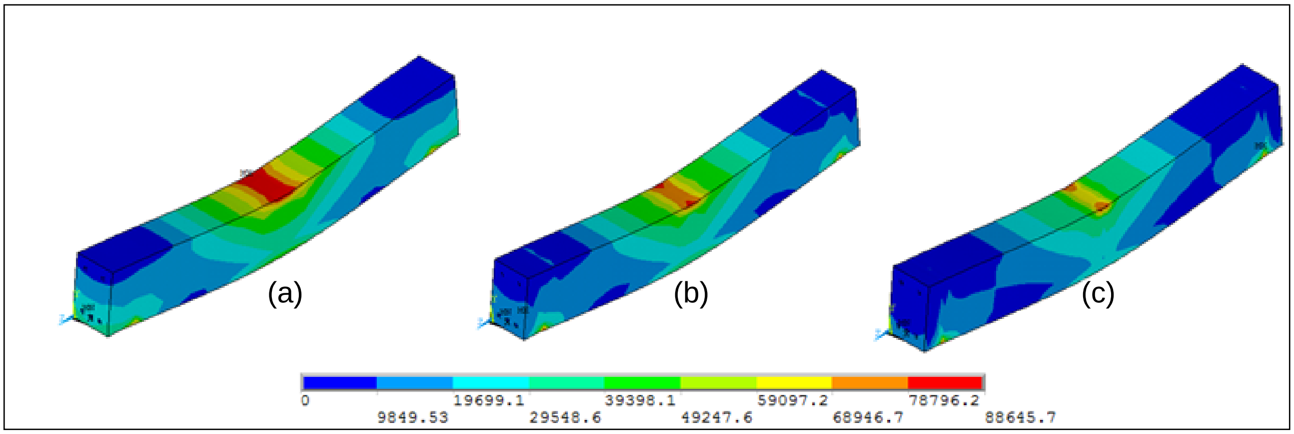


Figure 7 Stress Intensity at fail level for (a) CONVEN, (b) SSSSRS, (c) DSSSRS

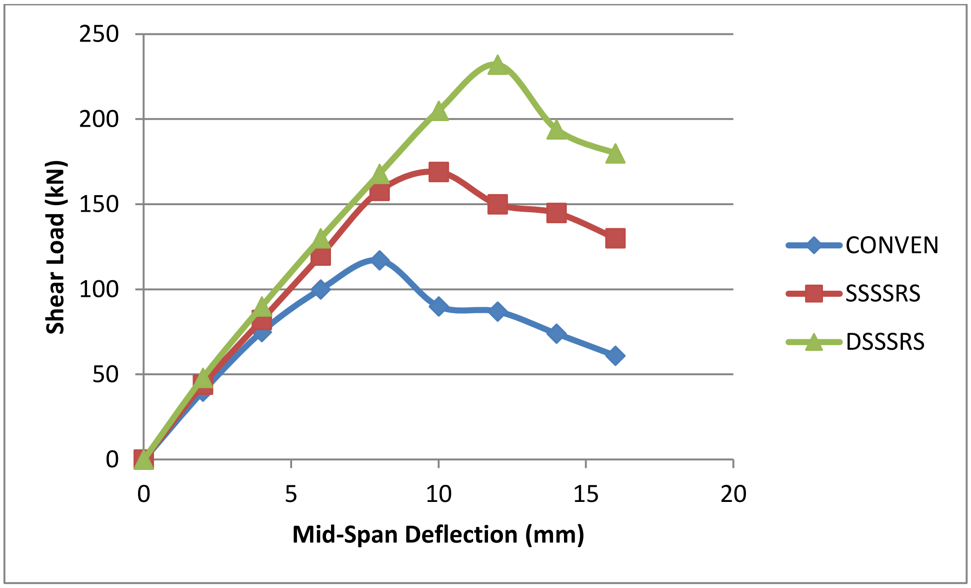


Figure 8 Comparison of Finite Element Performance of all Specimens

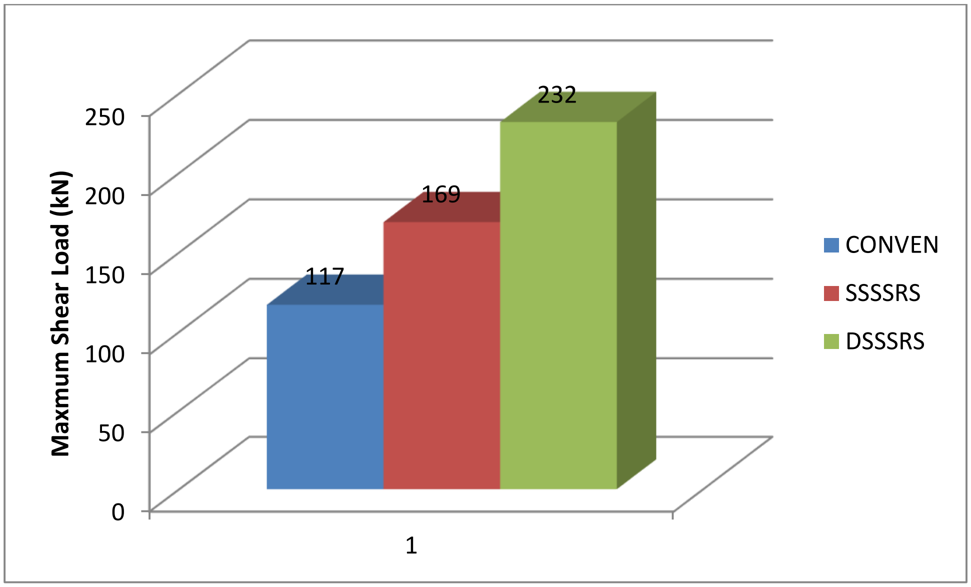


Figure 9 Maximum Shear Loads of all Specimens

Table 2 Finite Element Simulation Results for all Specimens

Specimens	Max. Shear Load (kN)	Max. Mid-span Deflection (mm)	Type of Failure
CONVEN	**117**	**8**	**Shear Failure**
SSSSRS	**169**	**10**	**Shear Failure**
DSSSRS	**232**	**12**	**Shear Failure**

According to stress intensity results that shown in Figure 7, it can clearly see that with applying continuous shear reinforcement system stress concentration problem will avoided. Accordingly, higher material capacity can be achieved in order to have an economic design. At the same time which stress concentration in critical area is less in specimens with continuous shear reinforcements, higher capacity of load bearing can be observed as shown in Figure 9. With using continuous shear reinforcement system the loads and stresses transferring can be done in an optimized way since both main reinforcement bars and shear bars are properly cooperate to transfer loads with high performance approach. All performance improvements are shown and compared in Table 2.

5.0 CONCLUSION REMARKS

Test results of this study have clearly indicated that the use of continuous rectangular spiral reinforcement can provide enhanced bearing capacity and improved shear performance in shear-critical beams Further, an advanced rectangular spiral reinforcement that has two continuous element of links has also been presented and tested as shear reinforcement. Beams with spiral reinforcement "Single Square Spring Shear Resistance System" (SSSSRS) spacing at 80 mm exhibited 14.4% increased shear capacity with respect to the corresponding beams with stirrups, respectively. Furthermore beams with advanced spirals "Double Square Spring Shear Resistance System" (DSSSRS) spacing at 80 mm exhibited 19.8% increased shear capacity with respect to the corresponding beams with stirrups, respectively.

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