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Numerical study for the effect of hairpin shaped shear reinforcement on one-way shear capacity of reinforced concrete beams

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Abstract. This study investigates the effectiveness of using Hairpin shaped stirrups to increase the shear capacity of beams and slabs. The hairpin system consists of inverted U-shape stirrups welded to flexural corner rebar. Previous research works proved the increase of the hairpin system in increasing the two-way shear capacity compared to conventional punching reinforcement. However, the system's ability to increase the shear capacity of beams has not been explored. This paper presents the results of Finite Element simulation of two beams performed using ABAQUS Software; one beam is reinforced with conventional shear stirrups, and the other is reinforced with hairpin stirrups. The load capacity, deflection and damage pattern of the two beams were compared. Results showed that beams reinforced with hairpin stirrups have higher load capacity and ductility compared to beams with conventional stirrups. However, the reinforcement type had little effect on the shear damage pattern.

Keywords: Finite Element Method, One-way Shear Capacity, Hairpin Reinforcement, Reinforced Concrete, non-linear analysis, volumetric elements.

1 Introduction

Concrete have been always known for its high compressive strength, and very weak tensile capacity. Reinforcing steel bars have been used to compensate the weakness of concrete, knowing that Steel have a very high tensile strength, rebars are mostly used in regions where concrete is subjected to tension. Reinforced concrete elements have many modes of failure, the most frequent ones are Flexural (mostly brittle flexure), tension, compression (in the compressive chord), or shear failure.

The main interest in this research is the Shear failure. The shear failure is usually brittle and sudden with little or no warning. The type of failure caused by these shear forces is usually inclined crack that tend to propagate throughout the concrete, usually from the area under tension towards the area under compression [1], as shown in Figure 1. These cracks are not always easy to detect since they are often not visible when they occur.

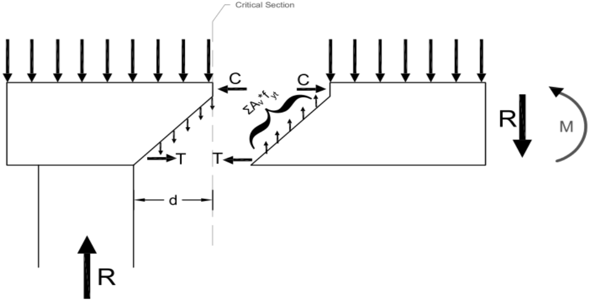

Fig. 1. Shear failure propagation

Many factors affect the shear failure mechanism such as the cross-sectional dimensions, nature of loading (static, dynamic), and the material properties. To ensure an effective performance during its service life, reinforced concrete beams must have an appropriate and suitable safety margin to resist bending and shear forces. Tensile cracks may appear at the ultimate limit state when the combined effects of bending and shear may exceed the resistance capacity of the beam. One of the clear signs of shear failure in beams is diagonal cracks located near the supports and caused by excess applied shear forces. One-Way shear failure, often referred to as "shear failure", usually occurs in beams [2] and, occasionally, in Walls, slabs, footings and other vertical members. Two-Way shear failure, often referred to as "punching shear failure", tends to occur in horizontal concrete members such as slabs, footings and foundations [3]. Shear forces are often resisted by concrete itself, in addition to Steel stirrups, Bent-up bars, or inverted U-shaped Reinforcement.
Nominal shear strength ACI318-14 [4]:

$$Vn = Vc + Vs \tag{1}$$

An approximate approach is provided by the ACI-318 Code for calculating V_C in members subjected to shear and flexure:

$$Vc = 0.17\lambda\sqrt{f'_c}\, b_w d \tag{2}$$

"λ" modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normal weight concrete of the same compressive strength" provided in ACI-318. Unless a more accurate approach is used "Vc" is provided through the following equation:

$$\left(0.16\lambda\sqrt{f'_c} + 17\int_w \frac{V_u d}{M_u}\right) b_w d \qquad (3)$$

The design of shear reinforcement in RC beams is bases on a truss analogy, as the forces inside the vertical ties is resisted by the Shear reinforcement. The capacity of shear reinforcement is denoted by **"Vs"**. V_s for shear reinforcement shall be computed by equation 4:

$$V_s = \frac{A_v \times f_{yt} \times d}{S} \qquad (4)$$

V_s for Inclined stirrups, making an angle of at least 45 degrees with the longitudinal axis of the member, shall be computed by equation 5:

$$V_s = \frac{A_v \times f_{yt} \times d \times (\sin \propto + \cos \propto)}{S} \qquad (5)$$

An "Inverted U" Reinforcing assembly used in Concrete Beams, is a bar bent to a U-shape and welded to 2 longitudinal parallel rebars. Several researches have been done on this type of shear reinforcement, concerning its enhancement on the punching shear capacity of Post tensioned slabs and "The PT slab capacity with hairpin-stud reinforcements were about 20% higher than with the shear-stud reinforcements" [5] [6].

The objective of this research is to study the behavior of an RC beam reinforced with U-shaped shear reinforcement, and another beam reinforced with conventional Stirrups. A four-point bending test will be simulated for both beams to study the shear capacity for each of them.

2 Numerical modeling

An analytical investigation was achieved on two types of reinforced concrete beams. The first one (S1) was provided with closed stirrups reinforcements and the second one (H1) was provided with Inverted U reinforcements in a beam ($h = 400mm \times B = 300mm \times L = 1500mm$) having six tension flexural reinforcement bars of diameter 32 mm in two layers compression flexural reinforcement bars of diameter 32 mm as the percentage of flexural reinforcement was increased to avoid pre-mature flexural failure. As for shear reinforcement, both beams were reinforced with a 10mm stirrups spaced at 190mm [7]. Figures 2 and 3 shows the different reinforcement distribution for each beam as modeled in ABAQUS. In addition, figures 4 and 5 shows the dimensions and distribution of reinforcement in each case.

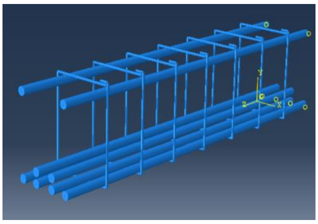

Fig. 2. "S1" rebar distribution

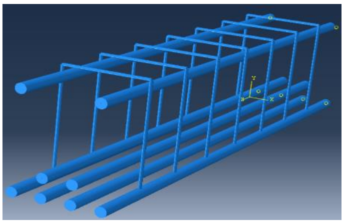

Fig. 3. "H1" rebar distribution

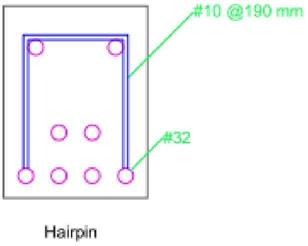

Fig. 4. Hairpin Beam section

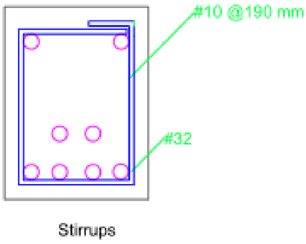

Fig. 5. Stirrups Beam section

The study was done using the finite element program "ABAQUS-CAE". Figure 6 shows the four-point bending test dimensions. Rebars were modeled as Truss elements "T3D2" for its simplicity and shorter analysis time, as there was no need to take into consideration explicitly the bond behavior between steel and concrete. A 3D stress element was used for concrete "C3D8R" to catch the full behavior of the beam. Figure 7 shows the 3-D view of the beam.

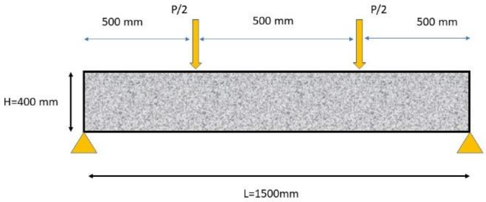

Fig. 6. Four point bending test dimensions

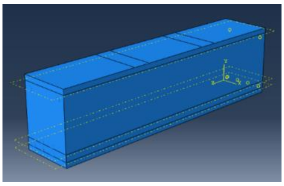

Fig. 7. Abaqus 3D beam model

The material model that will be used to describe the Plastic behavior is Concrete Damaged Plasticity (CDP), which is a plastic-based continuum model. Where it describes the behavior of the 30 MPA concrete used in the research. This model assumes and describes two failure mechanisms of concrete, Crushing in compression and cracking in tension. To define the plasticity some factors are imputed including, the "dilation angle= 36" that controls the amount of plastic volumetric strain developed during the plastic shearing, the eccentricity "e= 0.1" which defines the rate at which the hyperbolic flow potential approaches its asymptote. "K_c=0.667" which is the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian. Viscosity parameter = 0 used for visco-plastic regularization of the concrete constitutive equations [8]. Figures 8 and 9 shows the behavior of concrete in tension and compression when subjected to cyclic dynamic load [9,10]

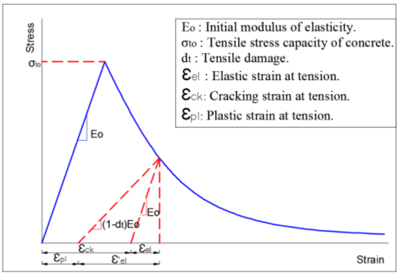

Fig. 8. Behavior of concrete in tension

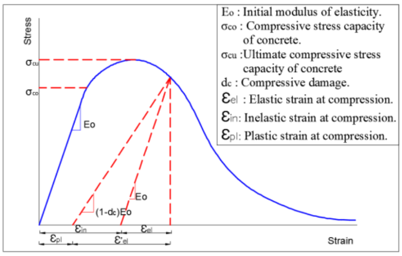

Fig. 9. Behavior of concrete in compression

As for steel rebars, the elastic-perfectly plastic behavior was assumed, which is acceptable for this analysis. A steel of a yielding strength of 420Mpa was used for both, the main steel and the stirrups A total Embedment constraint is assumed between concrete and steel since the bond behavior between concrete and rebar is out of research scope.

3 Results

The load deflection curve was plotted as shown in figure.10 to find the maximum load capacity for both cases. The beam with Inverted U reinforcements "H1" failed at a load of 23.6 t, whereas the beam with closed stirrups "S1" failed at 19.3t. As for ACI code regulations, the maximum load capacity was 20.5 t. the hairpin reinforcement has shown an enhancement in the ductility of the R.C. beam in shear, as Table 1 represents the max deflection sustained by both beams, the hairpin reinforced beam have an amplification of 25.6 % in the ductility.

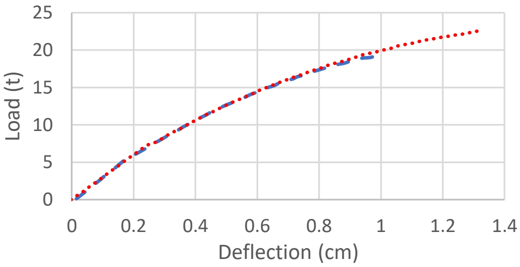

Fig. 10. Load-Deflection curve

Table. 1. Load capacity compared to ACI code.

	Beam "S1"	Beam "H1"	ACI Code
Maximum load (t)	19.3	23.6	20.5
Maximum deflection	10 mm	13.4 mm	-----

The damage presented below is the tension damage. The beam failure is initiated through an inclined tensile crack, which developed into a shear failure. Both beams failed in shear mode, but the beam with hairpin stirrups had a less damage concentration as shown in figures 11 and 12.

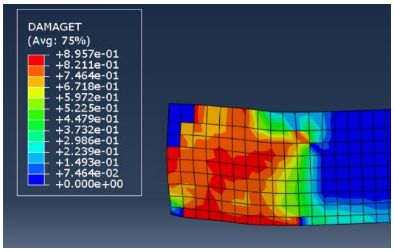

Fig. 11. Tensile damage near support for “H1”

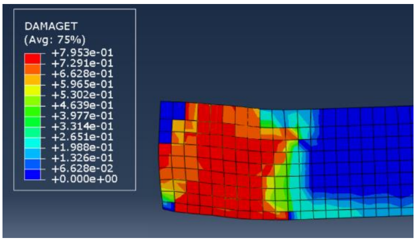

Fig. 12. Tensile damage near support for “S1”

3 Conclusions

Results of shear behavior of RC beams with Inverted U-shaped reinforcement were presented in this paper. The numerical results states that both models failed in shear. The test results with the Shear Stirrups were almost equal to those predicted by the ACI equation. The RC beam capacity with Inverted U-Shaped reinforcements were about 10.6 % higher than with the shear-Stirrups, and knowing that both beams had the same displacement at yield a 34 % enhancement was observed in the ductility computed as the % difference in the max deflection between the two beams. To obtain new equations governing the design of Hairpin reinforcement, Further research is needed. The test results have shown that the use of Inverted U reinforcement behaves structurally as good or better shear reinforcement than the Shear Stirrups.

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