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Nonlinear finite element study on the improvement of shear capacity in reinforced concrete T-Section beams by an alternative diagonal shear reinforcement

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ABSTRACT

In the study a new shear reinforcement configuration named as diagonal shear reinforcement (DSR) is proposed as an easily applicable, economical and alternative technique to improve the shear capacity and ductility of shear critical reinforced concrete (RC) beams under monotonic and cyclic loadings. For this objective a numerical nonlinear finite element (FE) study is performed by considering two tested beams with flexural and shear failure modes. These two tests results are first verified numerically then DSR is included to existing FE model to start a parametric study for highlighting the efficiency of proposed DSR shear reinforcement configuration.

The numerical results demonstrate that there is a significant increase in shear and ductility capacity of RC beams when proposed DSR is included. Moreover, with an increase in diameter and yield strength of DSR, the shear capacity further improves and failure mechanism shifts from shear to flexure. Thus, more ductile behavior for shear critical RC beams is achieved by the proposed DSR reinforcement configuration.

1. Introduction

Failure modes of reinforced concrete (RC) members such as columns, beams and shear walls are very important in seismic response of structures. The major failure modes of RC members are shear and flexure. These modes lead to a brittle or ductile response of structures. Because the shear failure is more brittle and sudden, shear capacity of RC members should be higher than flexural capacity of structures under seismic loads for achieving a ductile design [1].

Stirrups are generally used to increase the shear capacity of RC structural members and especially stirrups spacing are reduced for this purpose. Nevertheless short beams, which are deep with respect to their clear span are generally constructed due to architectural compelling requirements and due to structural reasons such as coupling beams connecting two structural walls. They can be exposed to large cyclic reversals of shear deformations under seismic loads resulting to a rapid deterioration of shear strength and stiffness of RC beams [2]. For such circumstances the stirrup densification may not be a sufficient solution to resist the shear stresses. In this case brittle shear behavior would be inevitable.

Moreover decreasing spacing of stirrups beyond the limits given in the specifications would lead to have insufficient bond between concrete and reinforcement due to the difficulties of casting concrete between densely planted reinforcements.

Inclined stirrups and bent-up longitudinal bars are defined as alternative shear reinforcements in many design codes such as ACI 318-14 [3] for RC beams. However; the shear reversals will make these reinforcement ineffective because inclined stirrups and bent-up longitudinal bars are located in one direction [2].

Diagonally oriented reinforcement is another solution to enhance the shear and moment strength of the coupling beams. It is however effective only if the bars are placed with a large inclination. Therefore, use of diagonal reinforcement is restricted to the beams having an aspect ratio of $l_n/h < 4$ in which l_n is the clear length and h is depth of beam [3].

Moreover there are several studies proposing a new technique to increase shear capacity of RC beams other than the shear reinforcements mentioned above. Among them the most current studies related with the paper, Corte and Boel [4], and Karayannis and Chalioris [5] investigated use of rectangular spiral reinforcement (RSR) by testing RC beams in a monotonic four-point test (Fig. 1a). Similar to application of spiral transverse reinforcement on RC columns,

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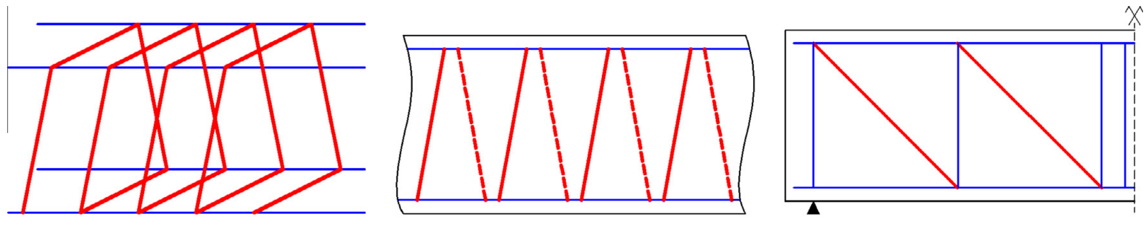

Fig. 1. Alternative shear reinforcement configurations from literature [4–7].

same procedure was applied to beams by surrounding longitudinal reinforcement. Test results indicated that the use of RSR enhanced shear performance of the tested beams.

Additionally, Yang et al. [6] studied effectiveness of spiral-type wire ropes as shear reinforcement (Fig. 1b). For this purpose three two-span reinforced concrete T-beams were tested under static loading in a four-point test setup. Test results demonstrated that the wire rope application was highly convenient to increase the ductility of beams failing in shear and to control the diagonal crack width.

In the research of Al-Nasra and Asha [7], swimmer bars as a new type of transverse reinforcement (Fig. 1c) with three types of connection (weld, bolt and u-link bolt) were investigated regarding their contribution to shear behavior of RC beams. Similar to above studies, an improvement in shear strength of tested RC beams was observed.

The major deficiency of existing new shear reinforcements for RC beams mentioned in the literature is that they have low cyclic performance under seismic loads due to the fact that they can be located only in one direction. Moreover, the implementation difficulties in practice may also cause to increase the labor and the budget.

On the other hand, there are two major experimental studies investigated cyclic performance of diagonal shear reinforcement. First of all, in the experimental study of Chalioris et al. [8] effectiveness of crossed inclined bars (X-bars) as joint shear reinforcement is investigated in exterior RC beam–column joints under cyclic deformations. In the second study, Dirikgil and Altun [9] conducted an experimental study to determine cyclic behavior of the diagonal shear reinforcement on RC short columns. The analogy behind diagonal shear reinforcement used in either RC beam–column joints or RC short columns is similar to the proposed diagonal shear reinforcement for RC beams in the study. Experimental results of both studies deduced that the diagonal shear reinforcement exhibited enhanced cyclic performance and improved damage mode. Moreover, the combination of stirrups and diagonal shear reinforcement resulted in improved hysteretic response and excellent performance capabilities of the specimens. However application of diagonal shear reinforcement proposed in the present numerical study for RC beams is slightly different from the applications given in the reference studies.

The first motivation of the study is to propose an alternative new shear reinforcement configuration to improve shear capacity of RC beams. Second objective of this study is to demonstrate how robust finite element (FE) analysis is in terms of representing actual nonlinear behavior of RC beams with this proposed shear reinforcement. Two beams whose responses were controlled by shear and flexure were selected from literature [10] and their results are employed to verify the finite element model (FEM).

There are a lot of numerical studies to investigate the behavior of RC beams. Moreover flexural and shear response of RC beams can be investigated numerically by using one dimensional (1D) fiber/layer [11–13], 2D plane-stress and plane-strain [14–18], and 3D solid [19–21] non-linear finite element formulations as current alternative numerical models. In these studies RC beams are generally modeled as 1D fiber or 2D plane stress FE models. However, in the present study a 3D FEM is used to increase the accuracy of numerical results.

Numerical analyses are carried out by commercial finite element software package, ABAQUS [22]. Once the verification of FEM is done with acceptable results, a parametric study is performed to show efficiency of the proposed shear reinforcement configuration.

2. Proposed new shear reinforcement configuration

The main essence of the proposed configuration is adding new diagonal steel bars between stirrups in the form of steel ties almost perpendicular to shear cracks. These new additional reinforcement bars are named as “diagonal shear reinforcement (DSR)”. DSR differs from inclined stirrups in a way that inclined stirrups are in the shape of closed rectangular form and confine longitudinal bars whereas DSR is placed diagonally near vertical surfaces individually in cross form. The application of DSR is showed in Fig. 2. The diagonal shear reinforcements are applied between stirrups in both left and right shear zones.

There are many significant advantages of DSR with comparison to the techniques proposed in current studies. Among them, DSR mainly is simple to form and apply, can be used as intended number, space and diameter, and facilitate concrete casting causing improvement of bonding between concrete and steel reinforcement. Moreover it works efficiently under cyclic loads [8,9] and improves shear capacity of RC beams significantly. DSR also does not require any extra labor supply and equipment therefore it is very cost effective.

3. Experimental study

Experimental test results are essential to verify the FEMs. Two experimental test results of Altin et al. [10] are selected for this purpose as a reference study. They tried to increase shear capacity of RC beams using external bonded steel plates. The main reason to select this study is that the study contains tests of both shear and flexure critical T-section RC beams. Moreover, T-section specimens also represent actual behavior of beams on real slab-beam systems.

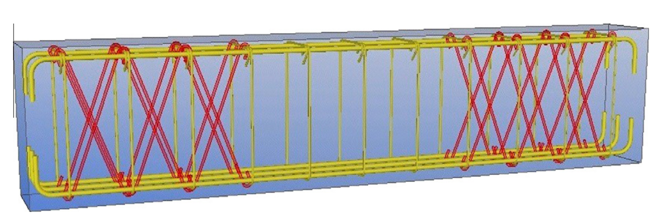

Fig. 2. Application of diagonal shear reinforcement (DSR).