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Structural behavior of RC membranes having inclined steel bars

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ABSTRACT

In seismic design, special care is needed when the shear force governs the response of a reinforced concrete (RC) element because this element undergoes stiffness degradation, strength deterioration and reduction in the energy dissipation capacity, as the cyclic loading increases beyond the yielding level. Experimental and analytical research has shown that this undesirable response can be controlled and even eliminated in the hysteretic load–deformation curves of a shear-dominant element if the steel orientation within the element is aligned in the direction of the applied principal stresses. However, in practice, it is quite difficult to orient the steel bars parallel to the principal stress directions due to geometric and construction limitations. In this study, the effectiveness of the steel reinforcement orientation on the structural response of RC shear membrane elements was investigated by analyzing the test results of four panels previously reported in the technical literature. The test results were also analyzed by using a compatibility-aided truss model. The experimental and analytical results indicated that the ductility and energy dissipation capacity of RC panels strongly depended on the reinforcement orientation. The results also showed that the hysteretic response of an RC panel did not vary linearly with the steel grid's orientation within the panel and there was a boundary where the deformability and energy dissipation of the RC panel increased rapidly.

1. Introduction

Reinforced concrete (RC) structures, when located in earthquake regions, are designed to withstand moderate seismic loading within the elastic range, and to absorb the energy of severe seismic loading using the plastic range. Therefore, to protect the life of occupants and prevent the collapse of structural elements, RC structures should be designed and proportioned to maintain their initial strengths and stiffnesses as well as show high energy dissipation capacitates in the event of high seismic excitations. Consequently, it becomes necessary to evaluate the inelastic responses and energy dissipation capacities of RC structures and to determine practical methods to enhance their seismic responses under earthquake loading.

Experimental and analytical studies have shown that when the shear force governs the response of an RC element, as in the case of an RC low-rise shear wall or RC beam with short-span-to-depth-ratio, the effect of shear on the element's cyclic response is thought to be responsible for the "pinching effect" in the hysteretic loops. This in turn causes the RC element to undergo stiffness degradation, strength deterioration and reduction in the energy dissipation capacity, as the cyclic loading increases beyond the yielding level. However, experimental research has shown that this undesirable "pinching effect" can be controlled and even eliminated in the hysteretic load–deformation curves of a shear-dominant element if the steel orientation within the element is aligned in the direction of the applied principal stresses. With such an orientation, RC shear-dominant elements can be designed to possess high energy dissipation capacities, similarly to RC flexural-dominant elements.

The effect of the steel bar orientation on the structural response of RC structures was first experimentally investigated by Park and Paulay [1] and Paulay et al. [2] who showed that the pinching effect in the hysteretic loops of coupling beams can be controlled by adding inclined shear reinforcement. Following this work, many experimental studies have been conducted in an attempt to assess the effects of the steel orientation on the cyclic response of RC shear-dominant elements. For example, Minami and Wakabayashi [3] and Tegos and Penelis' [4] conducted experimental tests which showed that short columns with inclined reinforcing bars had improved structural responses when compared to specimens with conventional reinforcement. In addition, Tsonos et al. [5] tested RC beam-column joint specimens with crossed inclined reinforcing bars. Their test results showed no appreciable strength degradation, and showed "spindle-shaped" hysteresis loops with large energy dissipation capacities. Hsiao and Chiou [6] tested low-rise shear walls with various steel grid orientations. Their experimental results showed that the pinching effect was remarkably reduced by reinforcement orientation. Shaingchin et al. [7] also conducted experimental study about shear walls to figure out influence of

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diagonal web. From the test, the specimens with diagonal web reinforcement exhibit less pinching effect in the hysteresis curves than the conventional one. Analytical research has also been conducted to predict the effects of the steel grid orientation on the cyclic response of shear-dominant RC elements. For example, Mansour et al. [8] and Lee and Kim [9] analyzed the structural response of RC membrane elements (panels) having inclined steel bars. The analytical results indicated that the structural responses of RC panels are influenced by the orientation of the steel bars with respect to the directions of the applied principal stresses. Hindi and Hassan [10] recommended a theoretical model to predict the behavior of diagonally reinforced coupling beams based on the results of technical literatures.

It is generally accepted that the inclined reinforcement improves the ductility and increases the energy dissipation capacity of an RC member. Experimental and analytical research [8,9] have confirmed that if the steel grid in a shear RC element is set parallel to the direction of the applied principal stresses, the cyclic response of the shear element is maximized to a limit that the shear-dominant element behaves similar to a flexural-dominant element. However, in practice, it is quite difficult to orient the steel bars parallel to the principal stress directions due to geometric and construction limitations (such as the shear span-to-depth ratio of a member).

This study investigates the effectiveness of the steel reinforcement orientation on the structural response of RC shear membrane elements (or panels) by analyzing the test results of four panels previously reported in the technical literature. The test results are analyzed by using a compatibility-aided truss model. Comparison between the experimental and predicted responses of the RC panels is also carried out. The results, reported herein, indicate that the ductility and energy dissipation capacity of RC panels strongly depend on the reinforcement orientation. The results also show that the hysteretic response of an RC panel does not vary linearly with the steel grid's orientation within the panel; in other words changing the steel grid orientation from an angle of 45° to 90° does not cause the energy dissipation or ductility of the panel to increase twofold. As such, this research also aims to find a trend, if any, between the variation in the energy dissipation capacity and ductility of RC shear-dominant elements with steel grid orientation.

2. RC panels used in investigation

To study the effects of the steel grid orientation on the response of shear-dominant structures, four full scale RC panels, previously tested by Hsu et al. at the University of Houston [11], are considered. The RC panels can be visualized as assemblies of larger wall-type and shell-type RC structures. Understanding the cyclic structural response of isolated elements (such as RC panels) is the first step in understanding the cyclic response of real structural components such as, for example, low-rise shear walls and deep beams.

A brief description of the four chosen RC panels is given below. Further details about the panels and the testing procedures can be found elsewhere [11]. The steel grid in each of the four chosen panels, CA2, CD2, CF2, and CE2, was oriented at 45°, 68.2°, 79.8° and 90°, respectively. The angle (α), used to define the steel grid orientation within each panel, is measured with respect to the direction of the applied principal stresses as shown in Fig. 1. This angle is defined between the direction of the longitudinal steel bars (or l-axis) and the direction of the applied principal compressive stress or (2-axis). In Fig. 1, the l–t coordinate is used to represent the longitudinal (l) and transverse (t) directions of the steel bars. All four panels were reinforced with two parallel steel grids and had an equal amount of steel percentage in both the longitudinal and transverse directions (i.e., $\rho_l = \rho_t$). The applied principal stresses on the panel are denoted by f_1 and f_2 in this research, based on the 1–2 coordinate system. The size of the test panels was 1397 mm (55 in.) × 1397 mm (55 in.) × 178 mm (7.0 in). Grade 60 steel bars (61494.5 psi yield stress) were used. The material properties and reinforcing ratios of the panels are given in Table 1.

The panels were subjected to reversed cyclic principal stresses in the horizontal and vertical directions of the panel. The two principal applied orthogonal stresses were maintained equal in magnitude and opposite in direction; this allowed the creation of a state of pure shear stress at a 45° direction to the applied principal horizontal and vertical stresses.

LVDTs were attached to each face of the test panels to measure the smeared (or average) strains as shown in Fig. 2. The measurement of the average strains in the horizontal, vertical and diagonal directions allowed the calculation of the shear strain at a 45° direction to the applied principal stresses.

2.1. Test results

The experimental hysteretic shear stress–strain curves (i.e., $\gamma_{45}^{\circ} - \gamma_{45}^{\circ}$) of the four panels are shown in Fig. 3. The figures show

Table 1
Specification of specimens and material properties.

Panel	f_c' (MPa)	ρ_l (/%)	ρ_t (%)	α (*steelangle*)
CA2	45.0	0.77	0.77	45.0
CD2	44.5	0.59	0.59	68.2
CF2	44.0	0.56	0.56	79.8
CE2	49.0	0.54	0.54	90.0

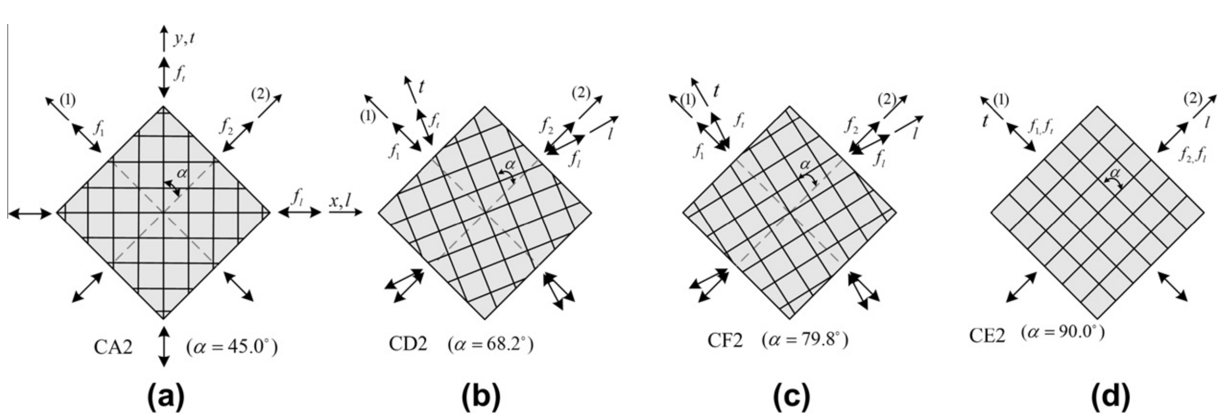

Fig. 1. Orientation of the steel bars of the test panels: (a) CA2, (b) CD2, (c) CF2, and (d) CE2.