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Effect of Type and Distribution of Shear Studs on the Behavior of Composite Steel-Concrete Shear Walls

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ABSTRACT

In this research the in-plane shear behavior of composite steel-concrete shear walls was investigated by taking into account the following variables: steel plate thickness, the spacing between shear studs, the shape and type of the shear studs and consideration of the minimum reinforcement in the wall section. Several finite element models were analyzed and numerical results of two models were verified with available experimental results in the literature. Results revealed that increasing the thickness of the steel plate increases the yield and ultimate shear strengths; moreover, increasing the spacing between shear studs reduces the shear resistance to some extent; furthermore, steel-plate composite (SC) walls with iron angles have higher yield and ultimate shear resistance than walls with studs; finally, the wall with the minimum reinforcement behaved better than the wall with no reinforcement in terms of ductility and shear strength.

1. Introduction

Shear wall systems are one of the most common and efficient lateral force resisting systems which are usually applied in moderate or high-rise buildings. These systems can provide adequate strength and stiffness for a structure against earthquake and wind loads with considerations of design requirements in terms of both ductility and strength. For so long, only reinforced concrete (RC) walls were used. However, during the last decades, different structural systems such as steel-braced frames, buckling-resistant frames [1-4] and SCs were both been used in order to evaluate the seismic performance in new structures and in strengthening of existing building especially in seismic areas. SCs are usually classified in two groups:

1-RC shear walls with steel or composite boundary elements (C-RCW).

2-Composite shear walls with steel plates (C-SPW).

In composite concrete shear walls with steel or composite elements (C-RCW), the RC wall is connected to the boundary elements with mechanical connectors such as shear studs, bolts or angles. Composite shear walls with steel plates (C-SPW) are usually comprised of a RC wall which is confined to one or two steel plates in one or two sides and are connected to mechanical connectors such as shear studs or bolts. In composite steel-concrete walls, steel plates are applied in both sides of the concrete core and the concrete core is not usually reinforced. Put it differently, SCs do not contain any vertical or horizontal reinforcements or shear rods. Steel plates are connected to the concrete core with shear studs. These studs act like shear connectors. Examples can also be found in some conditions where steel plates are connected to each other with transverse studs or diaphragms which act like a shear rod. The concrete core provides stability for the plates against buckling and steel plates contribute to the stiffness and ductility of the shear wall. This system is most efficient in structures with significant shear forces where usual calculations lead to thick walls which are not suitable as a result of architectural and economic considerations. Comparing to steel plate hear wall, the advantage of this system is that in steel-concrete walls local buckling occurs while in steel plate walls global buckling occurs.

2. Previous Research on SC Walls

Substantial research has been done in the last decades in the United States and Japan on the behavior of composite concrete-steel plate walls.

Usami et al. [5], examined the compressive response of SC walls with a particular attention to the buckling behavior of steel plates. The aim of the research program was to collect primary information regarding a suitable design method which could prevent non-elastic buckling in steel plates. In this experiment, four panels were tested under cyclic uniaxial compression of increasing magnitude. The primary variable was the ratio of shear stud spacing to plate thickness, $\left(\frac{B}{t}\right)$, which ranged from 20 to 50. Test observations of the plate buckling were compared to classical Euler buckling equation results. It was found that, when the buckling stress is less than $0.6f_y$, where f_y is the yield stress, Euler expressions give reasonably accurate results. For stresses greater than $0.6f_v$, the observed buckling stress is less than the classic Euler stress as a result of the non-elastic characteristic of steel. In other words, the steel which was applied in this experiment was not perfectly plastic, while it was assumed so. The other reason is the reduction of fixity in shear stud connections due to the increase in the compressive stress.

Takeada et al. [6] carried out experimental research on composite steel-concrete shear wallsin order to investigate the behavior of SC walls subjected to pure shear. This experiment focused on panels with web partitions (i.e., diaphragm). Each specimen was made of a concrete core which was connected to steel plates of the same size (Fig. 1a). The test variables were the thickness of steel plate, the number of partitioning webs and presence or the absence of shear studs. Researchers in this program used special instruments which were made for this purpose. (Fig. 1b). These instruments contained a device that simulated uniform distribution in in-plane shear loading. The loading jack, which loaded the reaction beams, provided equal tension in the rods. Rigid beams were attached to each side of the specimen to keep the boundary straight. A sliding surface was provided between the rigid



Fig. 1. Test setup a) shear wall panel specimen b) instruments of the pure shear experiment [6].

beam and the attachment to simulate the uniform load. The applied loads in each test were repetitively reversed and increased until the specimen failed. The typical failure mode of these panels involved cracking of the concrete, followed by buckling of the steel faceplates in the compression direction before reaching the yield stress, which is completed by the yielding of the faceplates in the tension direction and crushing of the concrete in compression. A simple quadralinear response model was developed in consonance with effective material moduli and an 'equivalent truss' analogy. While somewhat conservative, the model gave satisfactory estimations reasonably of cracking and ultimate stress capacities.

Ozaki et al, [7] carried out a research on 15 steel-concrete panels to explore the cyclic shear behavior of SC walls with the same instruments that Takeada et al. [6] applied in 1995. Two experimental research was carried out. One was the experimental study in which the influence of axial force and the partitioning web were explored. Another was that in which the influence of the opening was inquired. In the former program, nine specimens were subjected to cyclic in-plane shear. The test parameters were the thickness of surface steel plate, the effect of the partitioning web and the axial force. The test panels were 1200×1200 mm in plan dimension with a thickness of 200 mm. only two specimens had partitioning web around the center of the panel. The stud bolts were welded on the surface steel plate at intervals in which $(\frac{B}{t})$, was 30 [7]. Initially, the so-called ratio based on the findings of by Usami et al. [5] to prevent buckling of the surface steel before yielding.

The experimental results were compared with calculated results and good agreements between the calculated results and the experimental results were observed. The results demonstrated that, as expected, increasing the thickness of the steel surface steel plate, increases the elastic shear moduli, the post- cracking shear modulus, the yield strength and the maximum strength and ductility decreases. The axial force had no effect on the elastic shear moduli. However, the post-cracking shear modulus under the higher axial force slightly reduces. The cracking stress was clearly affected by the axial force.Notwithstanding, the yield strength and the maximum strength were not so much affected by the axial force.

In the latter program, six specimens having an opening were subjected to cyclic in-plane shear. This experiment focused on the presence of openings. FEM analysis was applied to supplement the experimental data and finally, a reduction ratio to account for the opening effect in design was proposed.

Ozaki et al. [7] developed analytical formulae, utilizing effective moduli for concrete, pre- and post-cracking stiffness and steel plate pre- and post-yield stiffness, combined with a post-cracking equivalent truss model, to describe the nominal response of the panels.

Sasaki et al. [8] tested seven flanged shear wall specimens, varying in height and thickness, subjected to in-plane lateral loading conditions. One specimen was subjected to a simultaneous axial load from two sides, and another varied in the layout of the stud anchor pattern applied. Specimens exhibited a marginally ductile response governed by yielding and followed by buckling of the web faceplates and compression shear failure of the concrete web. Story drifts of about 2.5% to 4.0% were attained. The authors concluded that the specimens exhibited superior performance compared to equivalent RC walls.

Katsuhiko Emori [9] developed a new system for SC walls. This model consisted of concrete- filled steel plate box. (Fig. 2). Test specimens were subjected to compressive and shear loading. The objective of this test was to inspect the structural characteristics of structural SC wall box unit with different thickness ratios of the steel plate. The test result was evaluated by a nonlinear finite element method.



Fig. 2. Concrete filled steel wall box [9].

Amit H Varma et al. [10, 11], examined the complex in-plane shear behavior of SC and out-of-plane shear behavior of SC walls. The in-plane shear behavior of steel plates in SC walls is different from that of RC walls with orthogonal grids of longitudinal and transverse rebar. In SC walls, steel plates contribute not only to their longitudinal and transverse strength, but also to in-plane shear stiffness and strength of the composite section. The in-plane shear loading produces principal tension and compression forces in the SC section and the principal tension causes the concrete to crack, subsequently, after concrete cracking, the sandwich panel behaves like an orthotropic plate with negligible stiffness in the principal tension direction but significant stiffness and compressive strength the principal in compression direction.

Amit H. Varma et al. [10], presented a design equation to calculate in-plane shear stiffness and strength. The equations were evaluated with experimental results and it was obtained that the presented theory was acceptable, despite some minor discrepancies. The authors concluded that the in-plane shear behavior of SC can be predicted reasonably and conservatively applying the tri-linear shear force-shear strain response based on the simple mechanics-based model.

Takeachi et al. [12], inspected the ease of construction of SC structures considering parameters such as the duration of construction, the amount of materials used and workability on a full-scale SC structural model. Walls, floors, columns and girders were all composed of concrete and steel plates with shear studs. (Fig. 3.). The model was subjected to vertical and horizontal loading. It was concluded that high resistance and ductility are benefits of SC structures. Additionally, the possibility of precast elements for SC structures will facilitate the construction procedure.



Fig. 3. Overview of SC structural system [12].

3. Specimens

Three specimens are modeled in ATENA 3D [13] to investigate the effect of steel plate thickness. In these specimens, which are denoted as T-3.2, T-4.5, T-5.5, steel plate's thickness is 3.2, 4.5 and 5.5, respectively. Diameter of shear studs are 9 mm and stud spacing between them is 135 mm in all specimens.

Models B-135, B-150, B200, B-300, B-600 denote specimens with variable shear stud spacing equal to 135, 150, 200, 300, 600 mm. model B-00 is a specimen without any shear stud. Steel plate thickness in all these models is constant and equal to 4.5 mm.

Angles are used to connect steel plates to concrete core in order to explore the effect of stud shape. This connection could be in one of two ways which are portrayed in Figs. 4a and 4b. In all these models, angle size is $40 \times 40 \times 4$ mm. Stud spaces are 200 mm in models NT-200 and NF-200 and 300 mm in models NT-300 and NF-300. In models NR-F and NR-T stud spacing is 200 mm and the varying parameter is connection type of angle and steel plates. Details are highlighted in Fig. 5. In model TS where hoops are used as steel stiffeners, the hoop spacing is 200 mm, steel plate thickness is 4.5 mm and hoop dimension is 40×4 mm. A model with minimum reinforcement is simulated to understand the effect of rebar on the behavior of composite shear walls. Stud spacing is constant and equal to 300 mm.



(b) Fig. 4. Connection of angles to steel plates, a) model NT, b) model N.



Fig. 5. Angles as studs, a) NT-200, b) NT-300, c) NF-300, d) NF-200, e) NR-F, f) NR-T.

4. Mechanical Properties of Materials

Concrete has a compressive strength of 42.8 MPa and 3.16 MPa tensile stress in all models. Stress-strain diagram of concrete is demonstrated in Fig. 6. Nonlinear behavior of steel plates and shear studs is considered through bi-linear Von Mises criterion. Steel plate's yield stress is 346 MPa and shear stud yield stress is 350 MPa. Similarly, yield stress of rebars is 210 MPa. In this research, the slippage between steel or studs and

concrete is modeled as an interface material. An interface material model is applied in order to simulate the interface connection surface between materials such as the connection of two concrete pieces or concrete and foundation. This model is confirming Moher-Columb defined to criterion. Interface material model's behavior in tension and shear is portrayed in Fig. 7. k_{nn} and k_{tt} denote normal elastic and shear stiffnesses, respectively which are estimated according to equation (1):

Equation (1):
$$k_{nn} = \frac{E}{t}$$
, $k_{tt} = \frac{G}{t}$

where E and G are elastic and shear moduli of material and t is the thickness of interface material. If the thickness of the interface material is taken as zero numerical errors will occur. On the other hand, significantly high stiffness values will also cause numerical instability. In this research, k_{tt} and k_{nn} are taken equal to 2×10^5 .



Fig. 7. The material model for interface behavior, in a) shear, b) tension

5. Loading

A static load is applied in an incremental manner with a magnitude of 0.417 MN/m^2 in each step. Uniform loading of the model is depicted in Fig. 8a and boundary conditions are presented in Fig. 8b.

6. Finite Element Model

Tetrahedron isoparametric elements are used to model concrete and shear studs. (Fig. 9a). This model has a great flexibility to be applied in prismatic or none-prismatic rigid materials. Steel plates are modeled using octagonal isoparametric elements (Fig. 9b).



Fig. 8. FEM model, a) loading, b) boundary conditions.



Fig. 9. FEM models a) FEM model of concrete and shear studs, b) FEM model of steel plate.

7. Verification

Specimens S400NN and S300NN of Ozaki experiment [12], were modeled in ATENA

3D [13] and the results were compared with experimental results. Figs. 10a and 10b demonstrate that numerical results are in a good agreement with experimental results.



Fig. 10. Verification of the numerical model, a) S400NN b) S300NN.

8. Numerical Results and Discussion

3 specimens are modeled in ATENA 3D inquire the effect of steel plate thickness. Force-strain diagrams are portrayed in Fig. 11a for models T-5.5 (steel plate thickness 5.5 mm), T- 4.5 (steel plate thickness 4.5 mm) and T-3.2 (steel plate thickness 3.2 mm).



Fig. 11. Force-strain relationship of models with various steel plate thickness and stud spaces.

Comparing the force-shear deformation relationship of the three models presented in Fig. 11a and taking into account the influence of steel plate thickness, the following results can be drawn:

As the surface steel plate becomes thicker, the slope of the force - strain curve in the elastic region and post-cracking region, yield strength and ultimate strength increases. Shear strain at the maximum force becomes decreases and thus the ratio of ultimate shear strain to yield strain becomes decreases and therefore ductility reduces. This phenomenon can be justified as a result of the constancy of the overall thickness of the panels in each instance; by increasing the thickness of the steel plates, steel shear capacity increases while the concrete shear capacity is not increased. Hence, by enhancing the thickness of steel plate of a SC panel, the concrete is susceptible to more damage, thus the shear strain at maximum strengths reduces and ductility decreases.

Fig. 11b, presents the force -shear deformation relationship of models which were analyzed to evaluate the effect of shear stud spacing. According to Fig. 11b the following results can be achieved:

Increasing the spacing between shear studs doesn't have a major effect on the slope of the force-deformation curve in the elastic region, while the slope of the curve in the post- cracking region is significantly reduced. As the shear stud spacing increases, yield strength and ultimate shear strength reduce, but the shear strain at the ultimate strength increases thus ductility increases. Increasing the spacing between shear studs reduces shear strength to some extent, yet it doesn't show much difference beyond a certain point, this may be attributed to concrete damage or buckling of steel plates due to excessive spacing between shear studs.

Figs. 11c and 11d exhibit that yield shear strength and ultimate shear strength are

mostly affected by changing the thickness of the steel plates rather than changing the shear stud spacing.

A model without shear studs has been contemplated in this paper which is labeled as "NO STUDS" in Fig. 11e. Although this model is not implemented in practice, shear studs or stiffeners are applied to connect steel plates to concrete. As expected, in the model without shear studs, yield shear strength and ultimate shear strength reduce considerably. If a model is considered in which the slippage between steel plate and concrete is ignored, the connection is assumed to be perfect. Perfect model in comparison with previous models, has higher yield shear strength and ultimate shear strength as expected. All models of different shear stud spacing, are in a region between the perfect and NO STUDS case. (Fig. 11f).

Fig. 12 displays the analytical results of models in which the iron angles have been applied as shear studs and are connected to steel plates. Results reveal that increasing the spacing between angles results in a reduction in yield shear strength and ultimate shear strength decrease and an increase in ductility. In models which are connected to steel plates as portrayed in Fig. 4b. However, the effect of angles spacing is more significant. (Figs. 12a and 12b). Models having angles in comparison with models having shear studs of the same stud spacing have higher yield shear resistance and ultimate shear resistance. (Figs. 12c to 12d and Figs. 13a to 13b). Figs. 13c and 13d present the models with angles connected to steel plates similar to Fig. 4a which have higher yield shear strength and ultimate shear strength than models which have angles connected to steel plates similar to Fig. 2b.

Force-shear deformation diagrams for models with angles connected to continuous steel, are demonstrated in Fig. 13. In models with angles connected to the wall as presented in Fig. 4a, both ultimate shear strength and ductility increase. The difference in the yield resistance is not significant (Fig.13e). Comparison of models NR-T and NR-F with the NT-200 and NFshow that models which 200. have continuous iron angle connections have slightly lower shear strength.

No significant difference is observed in yield strength. (Figs. 13f and 14a). Comparison is

made between Figs. 14b and 14c where rebar is connected to steel plates as stiffeners and models with angles. The model with rebar compared to NR-T model, despite having approximately the same shear capacity has higher shear deformation capacity, but in comparison with the NR-F model has less ultimate shear strength. Fig. 14d displays the wall in which minimum reinforcement is used. It can be implied from Fig. 14d that applying minimum reinforcement increases ductility and shear strength.



Fig. 12. Force-strain relationship of models with angles of different type of connection to plates



Fig. 13. Force-shear deformation diagrams of models having various shape and connection type of angles to steel plates.



Fig. 14. Force-shear deformation relationship of various stud shapes.

9. Conclusions

In this research, the in-plane shear behavior of composite steel-concrete shear walls was inspected by numerical analysis of different models. Influence of steel plate thickness, spacing between shear studs, the shape and type of studs and the presence or absence of minimum reinforcement were inquired to study the composite shear walls behavior. The following results were obtained: Increasing the thickness of the steel plate, increases the slope of the stress-strain curve, the yield strength, and ultimate strength. The shear strain at the ultimate strength decreases, therefore, the ratio of the shear strain to the yield shear strain reduces and the ductility decreases.

Increasing the spacing between shear studs doesn't have a major effect on the slope of the force-deformation curve in the elastic region, while the slope of the curve in the post- cracking region is significantly reduced. As well as an increase in ductility. Increasing the spacing between shear studs reduces shear strength to some extent, but it doesn't show much differences beyond a certain point, this may be attributed to concrete damage or buckling of steel plates due to excessive spacing between shear studs.

Yield shear strength and ultimate shear strength are more affected by changing the thickness of the steel plates rather than changing the shear stud spaces.

Models having angles in comparison with models with shear studs of the same stud spacing, have higher yield shear and ultimate shear resistance.

Applying minimum reinforcement in walls increases ductility and ultimate shear strength.

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