Ultimate Anchorage Capacity of Concrete Filled Steel Box Connection as Footing
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Introduction

Damage due to recent earthquakes has resulted in an increased conservatism in the design of piles and pile-to-pile cap connections. In contrast, current recommendations produce connection detailing which result in high levels of congestion of steel reinforcement in pile cap, which make extremely difficult to construct according to designer’s recommendation.

By considering this point, a new type of footing, concrete filled steel box (CSFB) connection as footing, is presented. Steel concrete sandwich structure is a relatively new form of structural system. This form of structure has the potential to fully utilize strength of both steel and concrete with help of composite action such as confinement. It allows the prefabrication of large section in a factory, and enables rapid installation into main structure, dramatically reducing the fabrication cost and construction time. Steel faces act as permanent formwork during the construction and provide impermeable skins for the structure upon completion.

Our purpose in this study is to develop design method for the CSFB footing by using a 3-D nonlinear finite element program CAMUI, which the authors’ group has developed. Therefore we can take part in the development of simple and economical hybrid structure with excellent mechanical properties.

First of all, numerical simulation, with the help of 3D nonlinear FEM program, of experimental specimens was carried out. The experimental program included five specimens were conducted in two phases. First phase included two specimens subjected to axial loading on column. The variable parameter for the first phase is concrete depth under the column. Second phase included three specimens subjected to monotonic loading perpendicular to longitudinal axis of column. The variable parameter for the second phase is column insertion length. After confirming the reliability of 3D nonlinear FEM program, parametric analysis was carried out and these parameters are insertion length, concrete strength, box size, column size, column length and box tube thickness. In this paper the effect of these important parameters are closely observed that will be useful for the development of design method of this type of footing.

FEM ANALYSIS

Constitutive Model of Materials

For un-cracked concrete and steel, elasto-plastic fracture model is used. The elasto-plastic fracture model divides concrete nonlinearity into continuum damage and plasticity, and this model is also very suitable for steel. The adopted failure criteria that acted in agreement with Niwa’s model in tension-compression zone and Yamada’s model in tension-tension region were extended to three-dimensional criteria by satisfying boundary conditions. For cracked concrete until peak, Vecchio and Collins model is used but for post peak, fracture energy concept was used. Fracture energy concept will be modified to predict the post peak behavior of the confined concrete with steel.

When crack occurs, a local coordinate system based on each crack plane is defined. In the case of 2 cracks occurring, two local coordinate systems arranged to share a parallel axis at the intersection line between the two crack planes. Constitutive models are applied in the direction parallel as well as normal to the crack and to shear slip along the crack planes. Global stresses are calculated by superposing the stress calculated in each local coordinate.

Modification of compression softening model for cracked concrete

The numerical solution of the finite element method using the smeared crack model is generally affected by the element size when the strain softening material model is adopted. This poses a severe problem to solve the post peak behavior of concrete structures. One solution of the problem was suggested by Nakamura is to adjust the stress strain relation according to the fracture energy balance in terms of element size. This is why; the fracture energy is treated as a material property and is kept constant in localized element regardless of element size. As we also know that post peak behavior of confined concrete varies with level of confinement. So by keeping these points in mind the fracture energy equation is modified in such a way that it should be a function of lateral conining stress. After peak stress, the effect of crack on compression softening is considered by the linear descending line. Reduced compressive stress has a limit that is 10% of the confined compressive strength. The gradient of strain softening is defined by compressive fracture energy.

\[ G_p = 8.8 \times (f'_{cc})^a \]  \( f'_{l/c} \)  \( f'_{l} \)  \( f'_{c} \)

\[ (1) \]

Where,

- \( f'_{cc} \): Confined concrete stress = \( f'_{c} + 4.1\times f_l \)
- \( f_l \): Lateral confining stress (average of two lateral stresses from 3D analysis)

Eq. (1) is modified form of Nakamura’s equation. The modification is change of \( f'_{cc} \) to \( f'_{cl} \) and “0.5” is changed to variable form i.e. \( a + b \times f'_{cl} \). These two
terms are modified because of following reasons. Fracture energy increases with the increase of confinement. The equation should be valid for both confined and unconfined concrete e.g. for confined concrete, the second term \((b f_l / f_c')\) will be added to “a” (because “\(f_l\)’ will be compressive and sign convention is positive for compression). But on the other hand, for unconfined concrete, the second term \((b f_l / f_c')\) will be subtracted from “a” (because “\(f_l\)’ will be tensile and sign convention is negative for tension). “a” and “b” are the parameters which are determined by trial and error technique. In order to find “a” and “b” rather simple cases of confined concrete cases are chosen. Concrete-filled steel tube (CFT) cases subjected to axial compression are an ideal case to see the applicability of the post peak behavior with confinement. The limit strain for compression is calculated from Nakamura et al.

\[
\varepsilon_a = \frac{2G_{\rho}}{\sigma_{\text{peak}} \times l_{eq}} + \varepsilon_{\rho} \\
\varepsilon_a = \frac{\varepsilon - \varepsilon_a}{\varepsilon_{u} - \varepsilon_a} \\
\varepsilon = \sigma_{\text{peak}} \left[ \frac{\varepsilon - \varepsilon_a}{\varepsilon_{u} - \varepsilon_a} \right]
\]

Due to symmetry, only one eighth of the CFT column is analyzed. Symmetric boundary conditions enforced on the symmetric planes. The corners of CFT with square sections are assumed to be exact 90° and corner radii are not considered. The uniform compressive loading is applied to the top surface of the column directly. Specimens from previous studies, that show concrete crushing dominant failure, are analyzed by varying the parameters “a” and “b” in the proposed fracture energy equation. In order to find the value of parameters “a” and “b”, first of all value of “b” is assumed and “a” is varied. So in order to make our equation suitable for both confined and unconfined concrete, the value of “b” was assumed in such a way that \((a + b f_l / f_c')\) should become close to “0.5” value for unconfined concrete. Parameters that precisely simulate the post peak behavior of confined concrete are selected and then verified for other specimens. Furthermore, it can be observed from Fig. 1, Fig. 2 and Fig. 3 that with the increase of confinement, post peak part of the load strain curve becomes more ductile. So it means fracture energy increases with increase of confinement level. This was the basic reason of the modification of the fracture energy equation. After analysis it can be observed from Fig. 1, Fig. 2 and Fig. 3 that for \(a = 0.86\), best simulation for post peak behavior of CFT column is achieved. So after trial and error method value of “a” and “b” were decided that is 0.86 and 7 respectively.

**Experimental program**

Experimental program consists of two phases. First phase was carried out to conduct the reliability of non linear finite element program (CAMUI) for axial capacity and second phase was carried out to conduct the reliability of the program for moment capacity. Phase 1 consists of two specimens. The notations S_37 to S_106 will be used for the specimens. The principal variable of the test specimens was concrete depth under the column. The steel box and column dimension are the same for all the specimens. Fig. 4 presents the dimensions of the tested specimens of Phase 1. Axial loads were applied through inserted square mortar filled steel tube as the column. Phase 2 consists of three specimens. The notations A1, A2 and A3 will be used

![Fig.1](image1.png)

![Fig.2](image2.png)

![Fig.3](image3.png)

![Fig.4](image4.png)

<table>
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<th>Table 1. Specimen details for Phase 2</th>
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<td>Specimens</td>
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for the specimens. The principal variable of the test specimens was insertion length of the pile. The details of experimental specimens for Phase 2 are given in Table 1. The column size and material strength were the same for all the specimens. Fig. 5 presents the dimension of the tested specimens of Phase 2. Bending moment was applied through the inserted pile. The inner pile was mortar filled circular steel tube, while the outer pile was circular steel tube. The concrete filled steel box together with the inserted inner pile was prepared first and the outer pile was set after wards. The gap between the inner and outer pile was carefully filled by mortar. In order to assure easy handling when the pile was fixed at the target location in the steel box we introduced the outer pile. The steel box was fixed by the connected steel beam which was fixed at its end.

**Numerical simulation of experimental specimen**

In order to show the reliability of the FEM simulation by CAMUI, the experimental results of Phase 1 and Phase 2 were compared with the simulation results. As the first step failure mechanism of the footings was observed. Crushing of concrete under the column is the dominant factor for the failure of the both specimens S_37 and S_106 as shown in Fig. 6 in which the stress-strain relationship at the gauss point 7 mm away from the column bottom show compression softening. From Fig. 7, it can be observed that experimental and analytical load displacement relationship shows good agreement in terms of ultimate load capacity. The higher stiffness of the analytical specimens A2 and A3 in comparison with the tested stiffness is probably because of the unexpected rotation of the outer pile due to incomplete filling between the inner and outer pile. This difference of stiffness becomes more prominent with the increase of peak load. It was also observed that with the increase of column insertion length, the ultimate capacity of the connection increased. This increase of peak load is because of increase in resistive moment.

**Parametric study on axial capacity of concrete filled steel box footing**

The analytical specimen is pile footings which comprises of concrete filled steel tube (CFT) column inserted in concrete filled steel box and are supported by four circular piles. The analytical models, as shown in
Fig. 9, are prepared by using commercially available software (3D Sigma). The specimen is symmetric, so in order to reduce the mesh number, one quarter of the specimen is modeled. In one analysis one parameter is variable and the rest of the parameters are kept constant.

**Effect of boundary conditions**

First of all, the pile footing was analyzed for two extreme boundary conditions. For one case piles were fixed and for 2nd case bond link elements are inserted between the pile and roller support to allow horizontal movement and rotation of the pile. After analysis, no difference was observed in terms of load displacement characteristics as shown in Fig. 10. So after this observation, the pile fixed at bottom was adopted for all analytical work of the pile footing under axial load.

**Effect of concrete depth under the column**

In order to see the effect of concrete depth under the column on the strength of pile footing, three cases with 100mm, 150 mm and 200 mm concrete depth were analyzed. After analyzing the specimens, it was observed that strength of the connection decreases with the decrease of the concrete depth under the column as shown in Fig. 11. This reduction of axial capacity is because of the reduction in peak stress of concrete under the column. The peak stress decreases with the decrease in the concrete depth is due to the increase in tensile strain in the direction normal to the peak compressive stress. It is believed that the tensile strain is caused as bending action in the steel box.

**Effect of concrete strength**

In order to see the effect of concrete strength on the strength of footing, four cases with different concrete strength were analyzed. The compressive strength of concrete for these cases was 24 MPa, 30 MPa, 40 MPa and 50 MPa respectively. After the analysis, it was observed that axial capacity of the footing increases with the increase of concrete strength as seen in Fig. 12. This increase of peak load is because of the increase in peak stress. Peak stress of concrete increased due to increase in concrete strength.

**Effect of steel box size**

In order to see the effect of box size on the strength of footing, four cases with different box size were analyzed. The box sizes for these cases were (800 x 800) mm, (1100 x 1100) mm, (1250 x 1250) mm and (1400 x 1400) mm respectively.

**Effect of column size**

In order to see the effect of column size on the strength of footing, three cases with different column sizes were
analyzed. The column sizes for these cases were (150 x 150) mm, (200 x 200) mm and (250 x 250) mm respectively. After the analysis, it was observed that axial capacity of the footing increases with the increase of column size as seen in Fig. 14. This increase of peak load is because of the increase in bearing area of concrete in which the compression crushing occurs.

Effect of insertion length

In order to see the effect of insertion length on the strength of connection, four cases with different insertion length were analyzed. The insertion length for these cases was 160 mm, 200 mm, 210 mm and 260 mm respectively. After the analysis, it was observed that anchorage capacity of the footing increases with the increase of insertion length as seen in Fig. 16. This increase of peak load is because of the increase in resistive moment. Resistive moment increases with the increase of resistive force and moment arm. The increase in resistive force is because of the increase in bearing area of concrete in which compression crushing takes place and bearing area is increased due to increase in length. Moment arm is also increased due to increase of insertion length. Increase of resistive force and moment arm can be seen in Fig. 17.

Parametric study on moment anchorage capacity of concrete filled steel box footing

The analytical specimens were footings which comprises of concrete filled steel tube (CFT) column inserted in concrete filled steel box and was fixed at bottom. Analytical models, as shown in Fig. 15, were prepared by using commercially available software (3D Sigma). The specimen is symmetric, so in order to reduce the mesh number, one half of the specimen was modeled. In one analysis one parameter is variable and the rest of the parameters are kept constant.

Effect of concrete strength

In order to see the effect of concrete strength on the strength of connection, four cases with different concrete strength were analyzed. The compressive strength of concrete for these cases was 18 MPa, 24 MPa, 36 MPa and 48 MPa respectively. After the analysis, it was observed that anchorage capacity of the footing increases with the increase of concrete strength as seen in Fig. 18. This increase of peak load is because of the increase in peak stress with the increase in concrete strength.
Effect of column size

In order to see the effect of column size on the strength of connection, three cases with different column sizes were analyzed. The column sizes for these cases were (150 \times 150) mm, (200 \times 200) mm and (250 \times 250) mm respectively. After the analysis, it was observed that anchorage capacity of the footing increases with the increase of column size as seen in Fig. 19. This increase of peak load is because of the increase in bearing area of concrete where crushing in compression takes place.

![Fig. 18 Relationship between peak load and concrete strength for moment anchorage](image1)

![Fig. 19 Relationship between peak load and column size for moment anchorage](image2)

Effect of box size

In order to see the effect of box size on the strength of connection, four cases with different box width were analyzed. The ratio of width to column section size for these cases was 2, 3, 4 and 6 respectively. After the analysis, it was observed that anchorage capacity of the footing remains almost same with the increase of box width as seen in Fig. 20.

![Fig. 20 Relationship between peak load and box width for moment anchorage](image3)

Effect of box thickness

In order to see the effect of box tube thickness on the strength of connection, three cases with different box tube thickness were analyzed. The thickness for these cases was 5 mm, 10 mm and 15 mm respectively. After the analysis, it was observed that anchorage capacity of the footing increases with the increase of box tube thickness as seen in Fig. 21. This increase of capacity is because of the better confinement of concrete surrounding the pile. Due to better confinement, peak stress is increased and as a result ultimate capacity increased.

Effect of column length

Since the loading point of the CFT column is at its end, a longer column gives a greater ratio of bending moment to shear force in the column at the location where the column insertion starts. In order to see the effect of column length on the strength of connection, four cases with different column length were analyzed. The column length, outside the footing, for these cases was 400 mm, 800 mm, 1200 mm and 1600 mm respectively. After the analysis, it was observed that for longer pile length, failure (concrete crushing around the column) takes place due to moment and for shorter pile length shear force is the dominant cause of failure. This can be observed in the Fig. 22 in which with the increase of column length, ultimate moment capacity of the connection becomes constant.

![Fig. 21 Relationship between peak load and box thickness](image4)

![Fig. 22 Relationship between moment anchorage and column length](image5)