Parametric Analysis of Concrete-Filled Steel Box Connection By using 3-D Finite Element Analysis

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The purpose of this study is to observe the effect of different parameters on the connection of steel box filled with concrete. The steel box is monolithically connected with steel beam, while a steel pile is inserted in the concrete. In order to develop the design method, effect of different parameters i.e. insertion length, material strength, box size, pile diameter and pile length were observed in the connection of steel box filled with concrete. After analysis, two types of failure mechanism were observed i.e. crushing of concrete and yielding of steel. Crushing of concrete dominant case takes place after the softening of concrete near the edge of pile. It was also observed that with the increase of concrete compressive strength the ultimate load of the connection varies non-linearly and with the increase of steel box size, ultimate capacity of the connection increases. Then it was found that by increasing the pile diameter the stress distribution around the pile increases, as a result, the ultimate load capacity of the connection increases. Then it was observed that for smaller pile length (outside of the steel box) shear force controls the failure but for longer pile moment controls the failure of the connection.
Key Words*: Steel Box Filled with Concrete Connection, Insertion of Pile, Concrete, Strength, Box size, Pile diameter, Pile length and 3D FEM Analysis*

1. Introduction

Steel concrete sandwich structure is a relatively new form of structural system. This form of structure has the potential to fully utilize respective 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. So after considering these points, we selected steel box filled with concrete for connection between two structural members such as beam and foundation pile in a bridge. It has advantage over steel structure because of cost factor and it is a better option as compared to reinforced concrete connection due to strength and construction time. Our purpose is to develop design method for connection by using a 3-D nonlinear finite element program CAMUI, which the authors' group has developed [1)]. Therefore we can take part in the development of simple and economical hybrid structure with high mechanical properties. In order to develop the design method for connection, parametric analysis is carried out. These parameters are pile insertion length, concrete strength, steel strength, steel box size, pile diameter, pile length and pile length (or moment to shear force ratio at end of pile outside the steel box). 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 connection.

The research on connection between steel beam and foundation pile by using concrete filled steel box was started by Emoto [2)]. The concrete filled steel box is a type of sandwich structure; however its failure mechanism is quite different from ordinary sandwich beams. The major finding was that failure of this connection occurs, when compression softening of concrete is caused by bearing stress from the steel pile. And other findings on shear connector effects was that the shear connector along the inserted length of pile enhanced the load carrying capacity of connection but shear connectors attached on skin plate of steel box had almost negligible effect on the strength of connection. Emoto also conducted the experiment and compared the experimental and 3D-FEM analytical results for this type of connection [2)] which shows the reliability of the FEM analysis.

The objective of this paper is to observe the effect of different parameters on strength of concrete filled steel box connection by using thus FEM analysis.

2. Specimen details for analysis

Economical and rational hybrid structures have been adopted recently. The connection of the hybrid rigid-frame bridge (**Fig. 1**) as shown in **Fig. 2** has been proposed due to construction conditions imposed to the bridge such as limited space. The rigid frame structure makes height of beam shorter, while the connection, which is a concrete filled steel box, makes the abutment size smaller.

2.1 Analytical model

Analytical model as shown in **Fig. 3** is prepared by using commercially available software. The connection is symmetrical in Y-Z plane so in order to reduce the mesh number one half of the connection is modeled. In one analysis one parameter is variable and the rest of the parameters are kept constant. Detail of analytical specimens is given in **Table 1.**

2.2 Constitutive Model of Materials

For uncracked concrete and steel, Elasto-plastic fracture model[3] 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 Aoyagi and Yamada's model in tension-tension region were extended to three-dimensional criteria by satisfying boundary conditions[3].

For cracked concrete until peak, Vecchio and Collins model[4] is used but for post peak, fracture energy concept is used[5].

When crack occurs, a local coordinate system based on each crack plane is defined (**Fig 4).** 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.

(1) Constitutive law of concrete with crack

The model is expressed as following relationship is expressed as the following relationship between σ , the tensile stress carried by concrete , and δ , the crack opening displacement.

$$\frac{\sigma}{f_t} = \left\{1 + \left(c_1 \frac{\delta}{\delta_0}\right)^3\right\} \exp\left(-c_2 \frac{\delta}{\delta_0}\right) - \frac{\delta}{\delta_0}\left(1 + c_1^3\right)\exp\left(-c_2\right) \qquad (1)$$

Where

c_1 : constant 3 .00 (in normal concrete)

c_2 : constant 6.93 (in normal concrete)

δ_0 : limit crack opening , 140 mm

f_t : Axial tensile strength of concrete

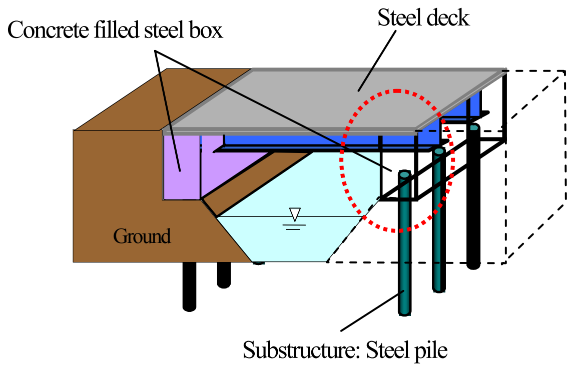

Fig 1 Hybrid rigid frame bridge

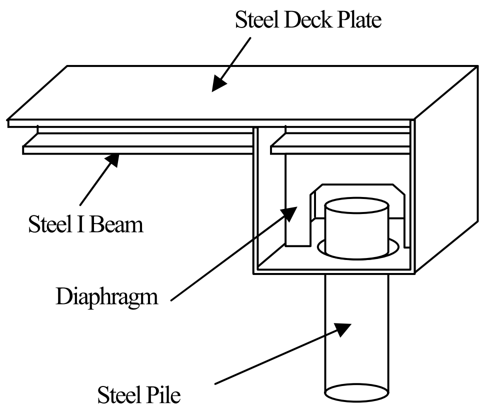

Fig.2 Connection of hybrid structure

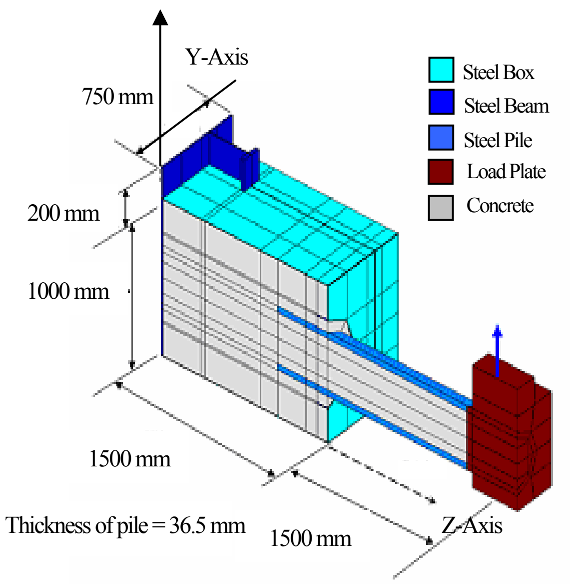

Fig.3 Analytical model

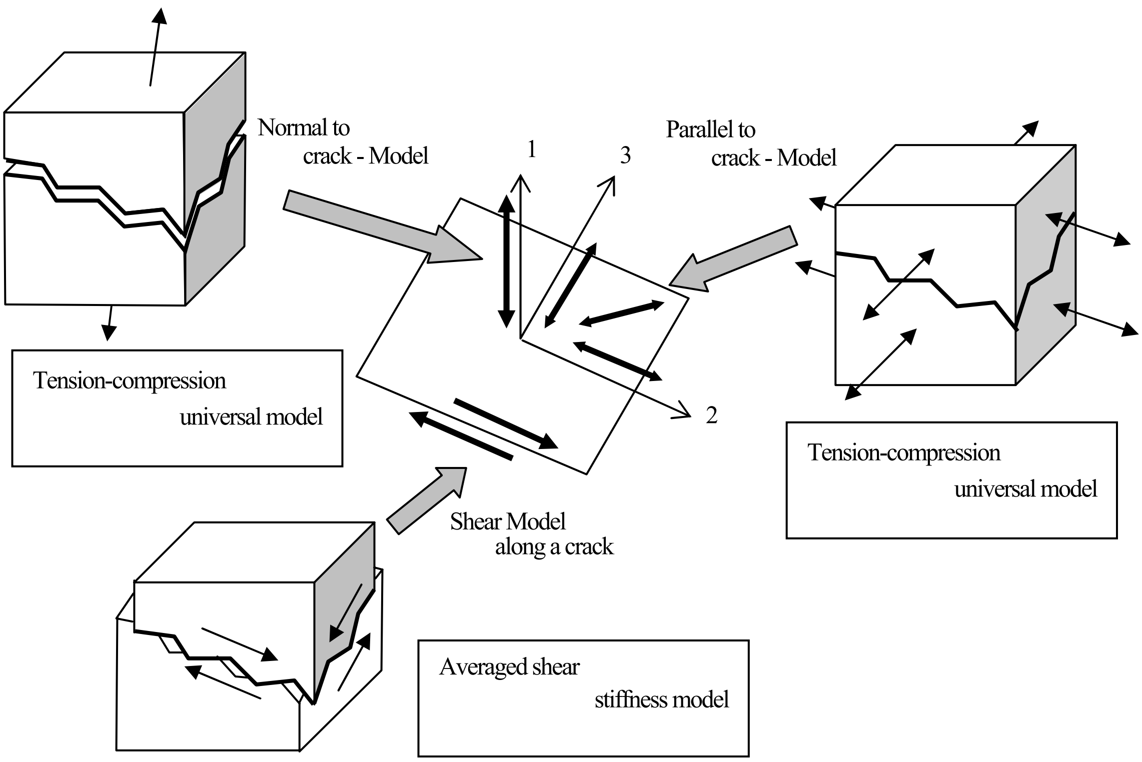

Fig 4 Constitutive model applied under one crack occurring

The Vecchio-Collins model was applied for the two dimensional concrete model prior to cracking in a plane parallel to the crack:

$$\varepsilon \leq \varepsilon_p$$

$$\sigma = f_c' \left[2\left(\frac{\varepsilon}{\varepsilon_0}\right) - \beta\left(\frac{\varepsilon}{\varepsilon_0}\right)^2 \right] \quad (2)$$

$$\varepsilon_p < \varepsilon \leq 2\varepsilon_0$$

$$\sigma = \frac{f_c'}{\beta}\left[1 - \left(\frac{\varepsilon - \varepsilon_p}{2\varepsilon_0 - \varepsilon_p}\right)^2\right] \quad (3)$$

Where

$\varepsilon_p = \varepsilon_o / \beta$

$\beta = 0.85 + 0.27\varepsilon_t / \varepsilon$

ε_t : Tensile strain in orthogonal to crack

ε_0 : Strain at compressive strength($2f_c/E_c$)

This model is expressed as the relation between principal stress and principal strain. Compressive strength is reduced according to magnitude of tensile strain in the direction parallel to crack.

The model in the shear direction was designed based on the average shear stress –strain model in cracked concrete proposed by Maekawa. This model is expressed by:

$$G_{cr} = \tau_{st} / \gamma_{cr} \quad (4)$$

$$G_t = 1 / \left(1/G_{cr} + 1/G_c\right) \quad (5)$$

$$\tau = G_t \times \gamma \quad (6)$$

Where

τ_{st} : Shear transferred stress at crack

γ_{cr} : Shear strain by relative shear displacement along to crack

G_{cr} : Shear modulus at crack plane

G_c : Shear modulus of concrete between cracks

G_t : Average shear modulus of cracked concrete

γ : Average shear strain in cracked concrete(γ_{cr})

τ : Average shear stress in cracked concrete

Shear transfer model proposed by Li and Maekawa (1989) was applied for the calculation of shear stiffness along a crack.

Table 1 Analytical specimen details

Analytical Speci-men	Insertion length (mm)	Concrete Strength (MPa)	Steel Strength of Pile (MPa)	Steel Box size (mm)	Pile diameter (mm)	Pile length (mm
1	450	24	347	1000	406.4	1250
2	604.5					
3	684.5					
4	854.5					
5	1110					
6	450	15.3	347	1000	406.4	1250
7		24				
8		30.6				
9		40.8				
10		51				
11		61.2				
12	450	24	300	1000	406.4	1250
13			347			
14			400			
15	450	24	347	1000	206.4	1250
16			400			
17			700			
18	450	24	347	600	206.4	1250
19				1000		
20				2000		
21				2400		
22	450	24	347	1000	406.4	1250
23				1400		
24				1800		
25	450	24	347	1000	606.4	1250
26				2000		
27				3000		
28				3600		
29	450	24	347	1000	206.4	1250
30					406.4	
31					606.4	
32	450	24	347	1000	406.4	200
33						600
34						1250
34						2000
35	Specimen 1 is analyzed which has Shear connector as bond between inserted pile and surrounding concrete					
36	Specimen 1 is analyzed by considering the friction element between inserted pile and surrounding concrete					

2.3 Bond link elements

Bond link element, in FEM Analysis, is 16 nodes have 4 gauss point element. The thickness of the element is considered zero. Two types of bond link element were used. One is the friction bond link element and the other is elastic bond element for shear connector of pile. For friction element, the relationship of shear stress-slip of the friction between steel and concrete considered the model used in analysis from the result of the punching shear test by Inomata et al[6]. For the shear connector, bond link element is the linear model using the stiffness derived from the formula of the previous study on shaped steel shear connector[7], which is actually used in this connection.

2.4 Boundary conditions

After adding bond link element, then boundary conditions for the connection is introduced, and this is shown in **Fig. 5**. The node, at which displacement is applied, is restricted in direction of the displacement.

2.5 Loading condition

Loading condition can be applied in two ways either applying the load or displacement. In this study, displacement is applied with an increment of 0.2cm. Point of application of displacement is shown in **Fig. 5**.

3. Results

3.1 Effect of insertion of pile

In order to see the effect of insertion length of pile on the strength of connection, five cases with 450 mm, 604.5 mm, 685.5 mm, 854.5 mm and 1110 mm insertion lengths were analyzed. After analyzing the specimens, the load displacement curves are shown in the **Fig. 6**.

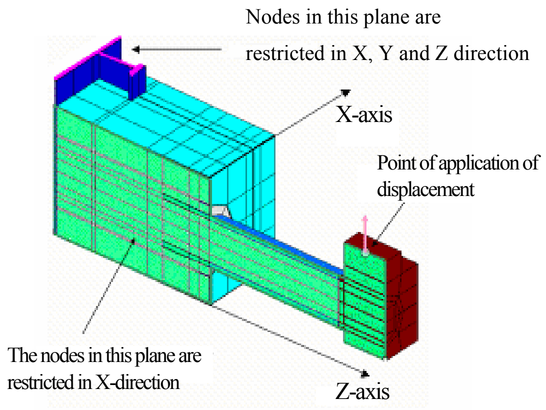

Fig.5 Boundary conditions of the connection

(1) Failure mechanism

After analysis, two types of failure mechanism were observed;

・Failure mechanism controlled by concrete crushing.

・Failure mechanism controlled by yielding of steel.

For first three insertion length cases (450 mm, 604.5 mm and 685.5 mm) the concrete crushing without the steel pile yielding controls the failure mechanism, while for the last two cases (854.5 mm and 1110 mm) the failure mechanism is controlled by the yielding of the steel pile.

(2) Occurrence of peak load

Peak load is reached after the softening in compression of the concrete surrounding the pile takes place. . This critical location is shown in **Fig. 7.** Stress-strain relationship of the concrete, surrounding the pile in the cases of different pile insertion length can show clearly compression softening as seen in **Fig. 8**. This figure also shows that the peak load occurs after the compression softening in concrete takes place.

From the load-deflection curve in **Fig.6**, it was also observed that strength of the connection increases with the increase of the insertion length. This increase in strength is due to increase in resistive moment, and resistive moment increases due to increase in liver arm. Concrete bearing stress distribution along the pile for different pile insertion length is shown in **Figs.9** and **10**. The lever arm of resultant of the concrete bearing stress shows the longer liver arm for the longer insertion length.

3.2 Effect of concrete strength

In order to see the effect of concrete strength on the strength of connection, six cases with different concrete strength were analyzed. The compressive strength of concrete for six cases was 15 MPa, 24 MPa, 30.6 MPa, 40.8 MPa, 51 MPa and 61.2 MPa respectively. After the analysis, it was observed that strength of the connection increases with the increase of concrete strength as seen in **Fig. 11**.

It was observed that the variation of peak load is not linear with respect to concrete strength. This nonlinear increase of peak load is due to tensile strain in the direction normal to the bearing compressive stress in the concrete along the longitudinal axis of pile. The tensile strain, which increases with the compressive strength, reduces peak compressive stress of the concrete, and thus variation of peak load becomes non linear as shown in **Fig. 12**.

3.3 Effect of steel strength

(1) Concrete crushing dominant case

Three cases with different steel strength of pile were analyzed. The pile steel strength for these cases was 300 MPa, 347 MPa and 400

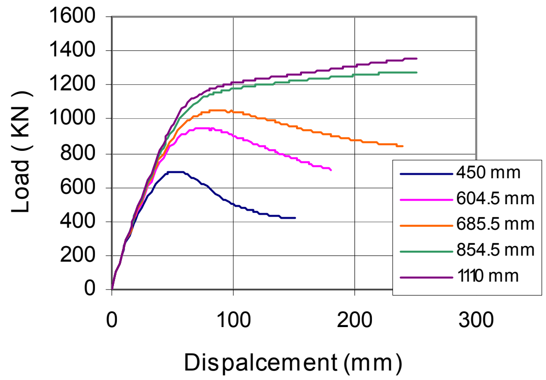

Fig. 6 Load-displacement relationship for different insertion length

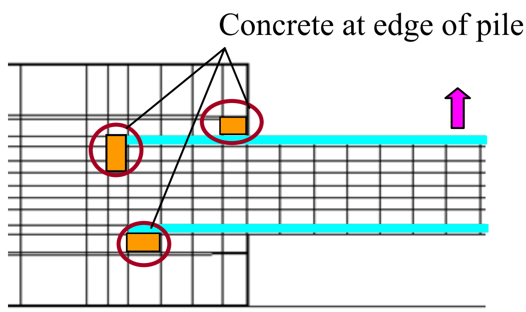

Fig.7 Location of compression softening in concrete surrounding the pile

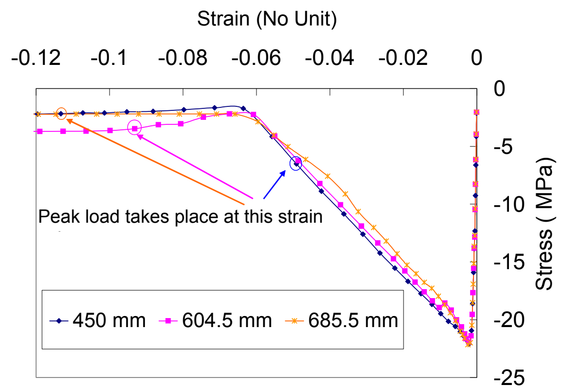

Fig.8 Softening in compression of the concrete surrounding pile in different cases of pile insertion length

MPa respectively. After the analysis, it was observed that by changing the steel strength has no effect on the strength of connection

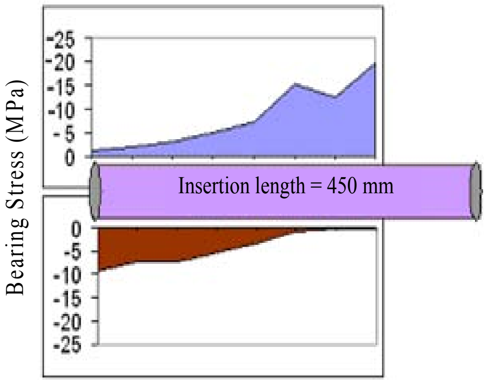

Fig 9 Concrete stress distribution along the 450 mm insertion length of pile

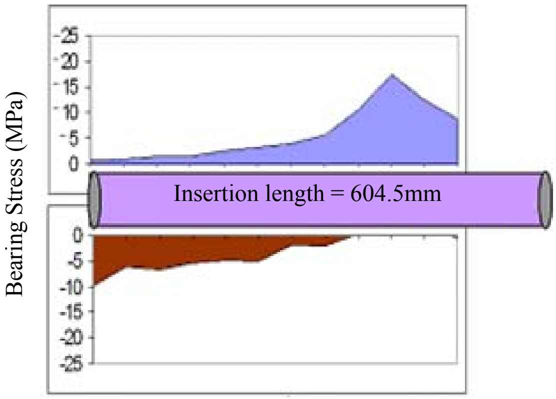

Fig.10 Concrete stress distribution along the 604.5mm insertion length of pile

unless the yielding of steel takes place. This can be observed from **Fig. 13** in which load-displacement curves for the different steel strength are almost the same.

(2) Yielding of Steel dominant case

If the yielding of steel takes place, then peak load is different among different steel strength. In order to prove this statement the specimen with 206.4 mm diameter was analyzed with different yield strength of pile. Smaller diameter is used to allow the yielding of steel pile. After analysis, it was observed that peak load increases with the increase in yield strength as shown in **Fig. 14**.

3.4 Effect of steel box size

In order to observe the effect of steel box width on the strength of connection, different sizes of steel box were selected for three diameters of pile 206.4 mm, 406.4 mm and 606.4 mm respectively. It was observed that ultimate load capacity of the connection decreases with decrease of the box width (see **Fig.15**). This decrease in strength is due to reduction of peak compressive stress of concrete surrounding the pile. This decrease in peak compressive stress is due to increase of the tensile strain in the direction normal to the compressive stress in the concrete along longitudinal axis of pile (See encircled portion of **Figs 16 , 17** and **18** to observe the increase in tensile strain as decreas-

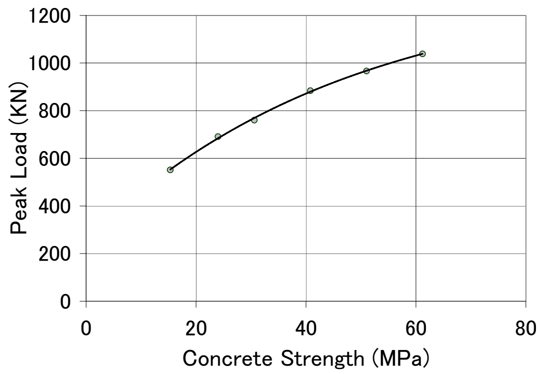

Fig. 11 Relationship between peak load and concrete strength

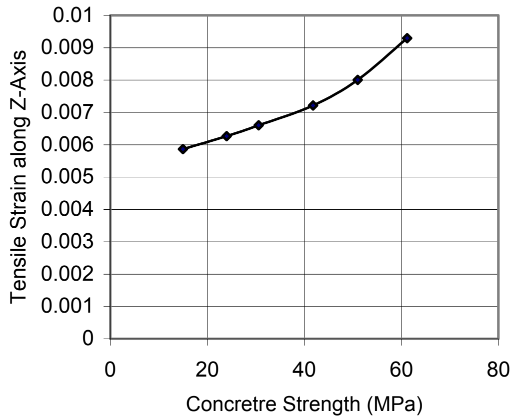

Fig.12 Relationship of tensile strain and concrete strength

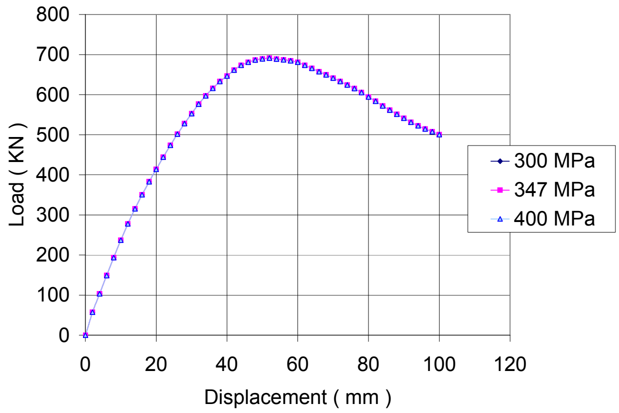

Fig.13 Load - displacement relationship for different steel strength when no yielding of steel takes place

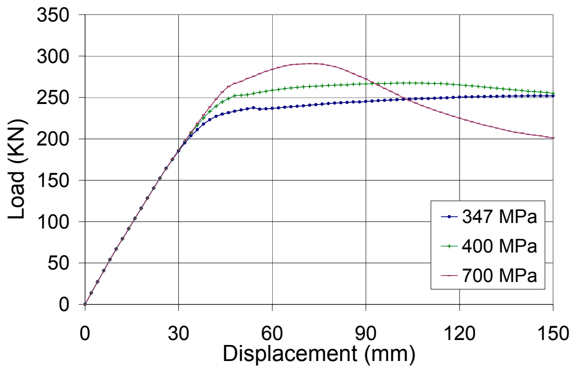

Fig.14 Load - displacement relationship for different steel strength when yielding of steel takes place

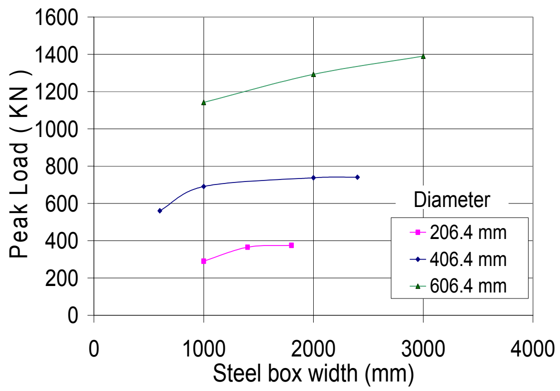

Fig 15 Relationship between peak load and steel box size

ing the box size.). It is also observed that when box size reaches to 5 times the diameter of pile, peak load becomes almost constant with respect to steel box size and it is shown in **Fig. 15.**

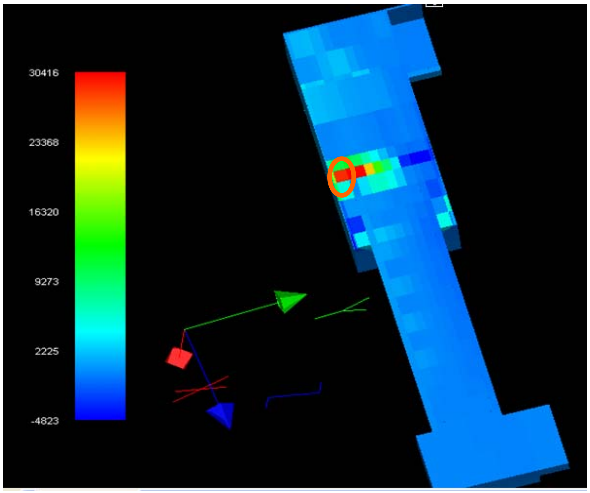

Fig 16 Tensile strain distribution along Z axis when box size is 600 mm.

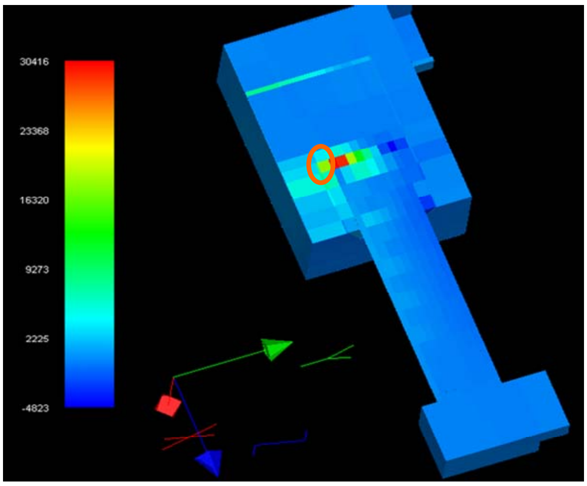

Fig 17 Tensile strain distribution when box size is 1000 mm.

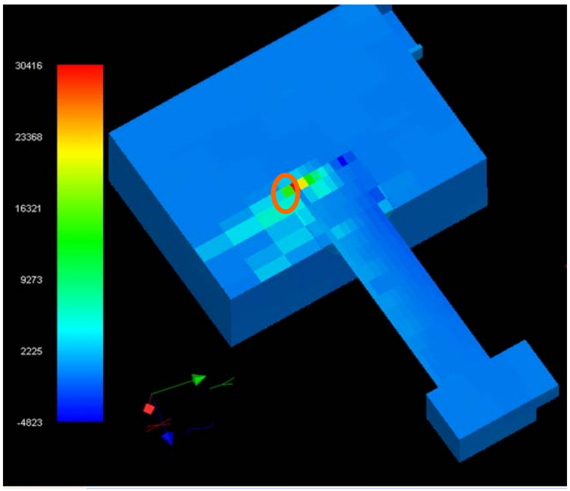

Fig 18 Tensile Strain distribution when box size is 2000 mm

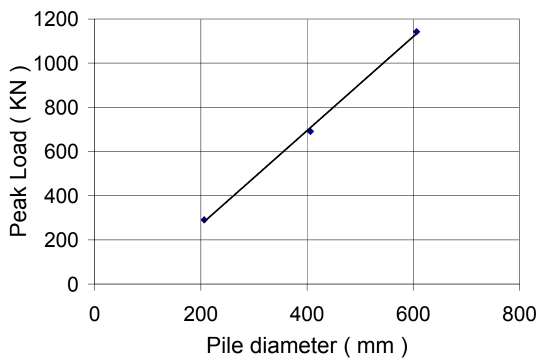

Fig.19 Relationship between peak load and pile diameter

3.5 Effect of diameter of pile

In order to see the effect of pile diameter on the strength of connection, three cases with 206.4 mm, 406.4 mm and 606.4 mm diameter were analyzed. The insertion length and box width for these cases are 450 mm and 1000 mm respectively. After analysis, it was observed that strength of the connection increases with the increase of the diameter as shown in **Fig. 19.** The area, on which stress acts, increases when the diameter increases. As a result the resultant of concrete bearing stress increases, and this causes increase in ultimate load capacity of the connection

3.6 Effect of pile length

Since the loading point o the steel pile is at its end, a longer pile gives a greater ratio of bending moment to shear force in the pile at the location where the pile insertion starts. In order to see the effect of pile length outside of the steel box on the strength of the connection, four cases with 200 mm, 600 mm, 1250 mm and 2000 mm pile length were analyzed. After analysis, it was observed that for longer pile length, failure (concrete crushing around the pile) takes place due to moment. And for shorter pile length shear force is the dominant cause of failure. This can be observed in **Fig. 20** in which with the increase of pile length, ultimate moment capacity of the connection becomes constant.

3.7 Effect of bond link element along inserted pile

At the end, the effect of bond between the inserted steel pile and concrete was observed. Shear connector and friction element are used as bond link element in two cases respectively. Shear connector is in form of ring around the steel pile. The width and height of shear connector, which is shaped steel, is 12 mm and 6 mm respectively and spacing between shear connectors is 120 mm. The arrangement of shear connectors is shown in **Fig. 21.** After analysis, it was observed that shear connector of the steel pile raises the capacity of the connection as shown in **Fig. 22,** which agrees with the result in previous study [2].

4. Model for prediction of ultimate load

On the basis of parametric analysis result, a simple expression is developed for calculation of peak load of the connection for failure mode without yielding of steel pile. Curve fitting technique is used to develop the formula for peak load of the connection

For simplicity, actual bearing stress distribution in concrete is considered as equivalent rectangular stress block, and the peak load, P, which is calculated from the resultants, R_1 and R_2, of the bearing stress at front and back sides of the pile can be obtained as follows (see **Figs.23** and **24**):

$$P = R_1 - R_2 \quad (7)$$

$$R_1 = \sigma_1 \times b_1 \times a_1 \quad (8)$$

$$R_2 = \sigma_2 \times b_2 \times a_2 \quad (9)$$

Step 1:

First step was to find the value of σ_1 and σ_2. These values are defined as follows;

$$\sigma_1 = \alpha_1 \times f'_c \times \Phi \quad (10)$$

$$\sigma_2 = \alpha_2 \times f'_c \times \Phi \quad (11)$$

And

$$\alpha_1 = 1.220 \times (f'_c)^{-0.294} \quad (12)$$

$$\alpha_2 = 0.245 \times (f'_c)^{-0.025} \quad (13)$$

Where f'_c = Concrete compressive strength in MPa, α_1, α_2 are reduction factors, which are less than 1. These factors decreases as the concrete strength increases because of the tensile strain in concrete produced along the longitudinal axis of pile.

Then considering the effect of box size, a Φ factor is included in the equation. This Φ is a function of steel box size and pile diameter as follows:

$$\Phi = A \times (1 - e^{-BW}) \quad (14)$$

Where W is width of steel box in "meter", and A and B are factors depending upon the diameter of pile as below:

$$A = 0.383 \times \ln(d) - 1.231 \quad (15)$$

$$B = -2.514 \times \ln(d) + 17.80 \quad (16)$$

Where d is the diameter of pile in "mm".

Step 2:

After finding the stress, then a_1, a_2 is determined by considering the pile diameter effect on the strength of connection as follows:

$$a_1 = a_2 = \gamma \times \text{Pile diameter}$$

where γ = factor whose value is also less than 1 and calculated by Eq.(11).

$$\gamma = 0.153 \times (d)^{0.271} \quad (17)$$

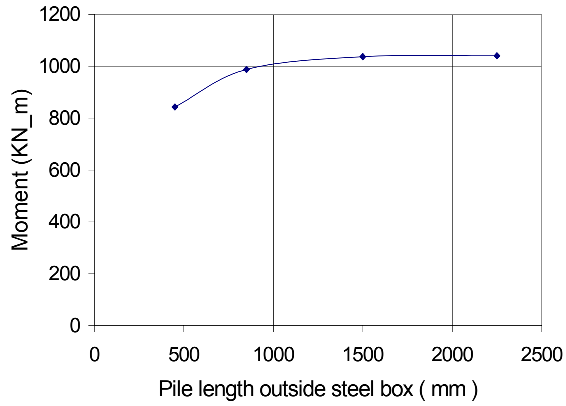

Fig.20 Relationship between ultimate moment and pile length outside steel box

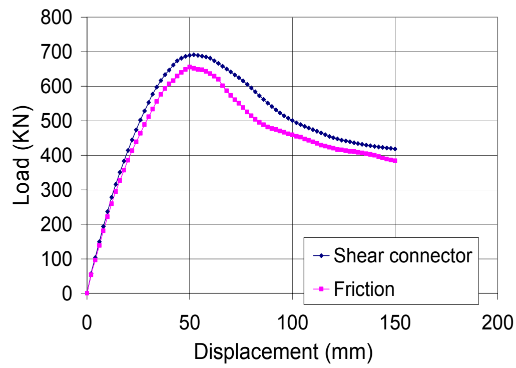

Fig.21 Load displacement relationship for different bond link element

Step 3:

Then values of b for each σ and a are calculated by the following equations:

$$b_1 = \beta_1 \times l \quad (18)$$

$$b_2 = \beta_2 \times l \quad (19)$$

Where l = insertion length of pile in (mm) and

$$\beta_1 = -0.518 \times \ln(l_p) + 4.433 \quad (20)$$

$$\beta_2 = -0.421 \times \ln(l_p) + 3.678 \quad (21)$$

Where l_p = pile length outside the steel box in "mm".

Step 4:

In order to include the effect of bond behavior between the inserted pile and concrete another factor ψ is used as follows:

$\Psi = 1$ with shaped steel shear connector is provided

$\Psi = 0.95$ without shear connector

Step 5:

Final equation will be

$$P = \Psi \times \Phi \times f'_c \times l \times (\alpha_1 \times \beta_1 - \alpha_2 \times \beta_2) \times \gamma \times d \quad (22)$$

Where P is in "N", f'_c is in "MPa", l and d are in "mm". The equation is only valid for those cases in which failure is controlled by moment. This means that this equation is only applicable for the range which is shown as the constant ultimate moment range in **Fig.20**.

5. Verification of model with FEM Analysis

The equation's results are compared with the numerical analytical results for the verification of the model in Fig. 25.

6. Conclusions

The objective of the study was to see the effects of different parameters on the strength of connection. These parameters are insertion length, concrete and steel strength, box size, pile diameter and pile length outside the box. From the analytical study, the following conclusion can be obtained.

After analysis, it was observed that by increasing the insertion length of pile, peak load increases. This increase in peak load is due to increase of resistive moment by surrounding concrete, in which bearing stress is more widely distributed in longer insertion case.

Ultimate strength of the connection increases nonlinearly as the concrete strength increases. This non-linear increase is because of increase of the tensile strain in the direction normal to bearing stress in concrete along the longitudinal axis of pile, which reduces the peak compressive stress in concrete.

There is no effect of steel strength on the ultimate strength of the connection provided that concrete crushing controls the failure mechanism of the connection before the yielding of steel pile takes place.

Ultimate load capacity of the connection decreases with decrease of the box size. This decrease in strength is due to decrease of the compressive peak stress of concrete surrounding the pile, which is caused by increase of tensile strain in the concrete.

Ultimate load capacity of the connection increases with the increase of the pile diameter. This increase is due to the increase of the resultant of concrete bearing stress distributed around the pile inside the steel box. For different pile length outside the steel box failure of the connection takes place because of bending moment or shear force. For longer pile the failure takes place because of moment.

Tentatively a simple model to calculate the peak load for the case caused by increase of tensile strain in the concrete.

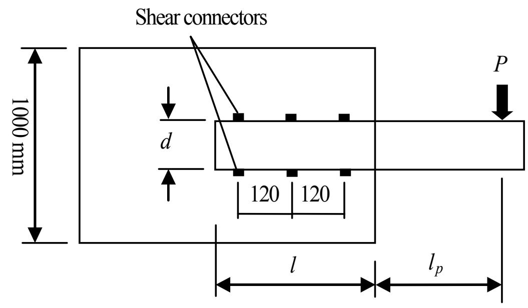

Fig.22 Arrangement of shear connectors

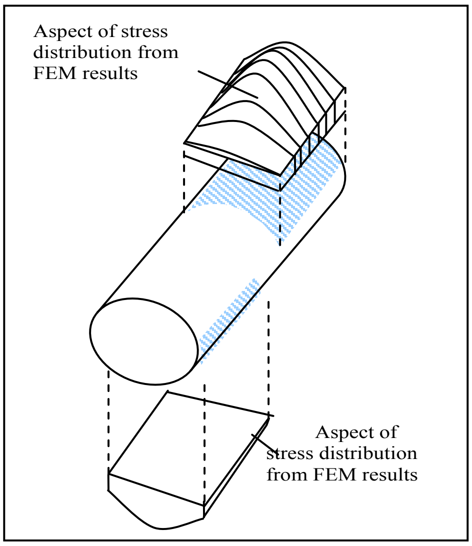

Fig.23 Aspect of stress distribution around pile

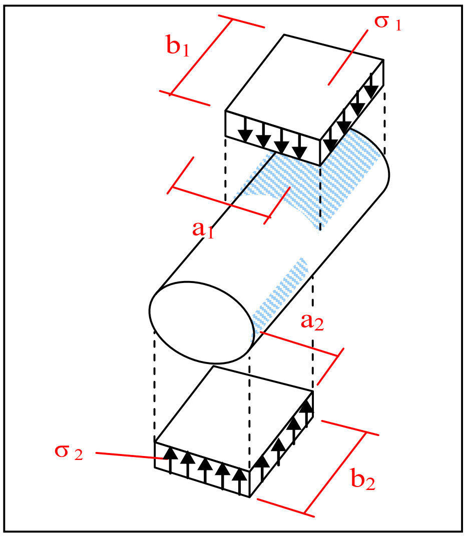

Fig.24 Assumed stress distribution around pile

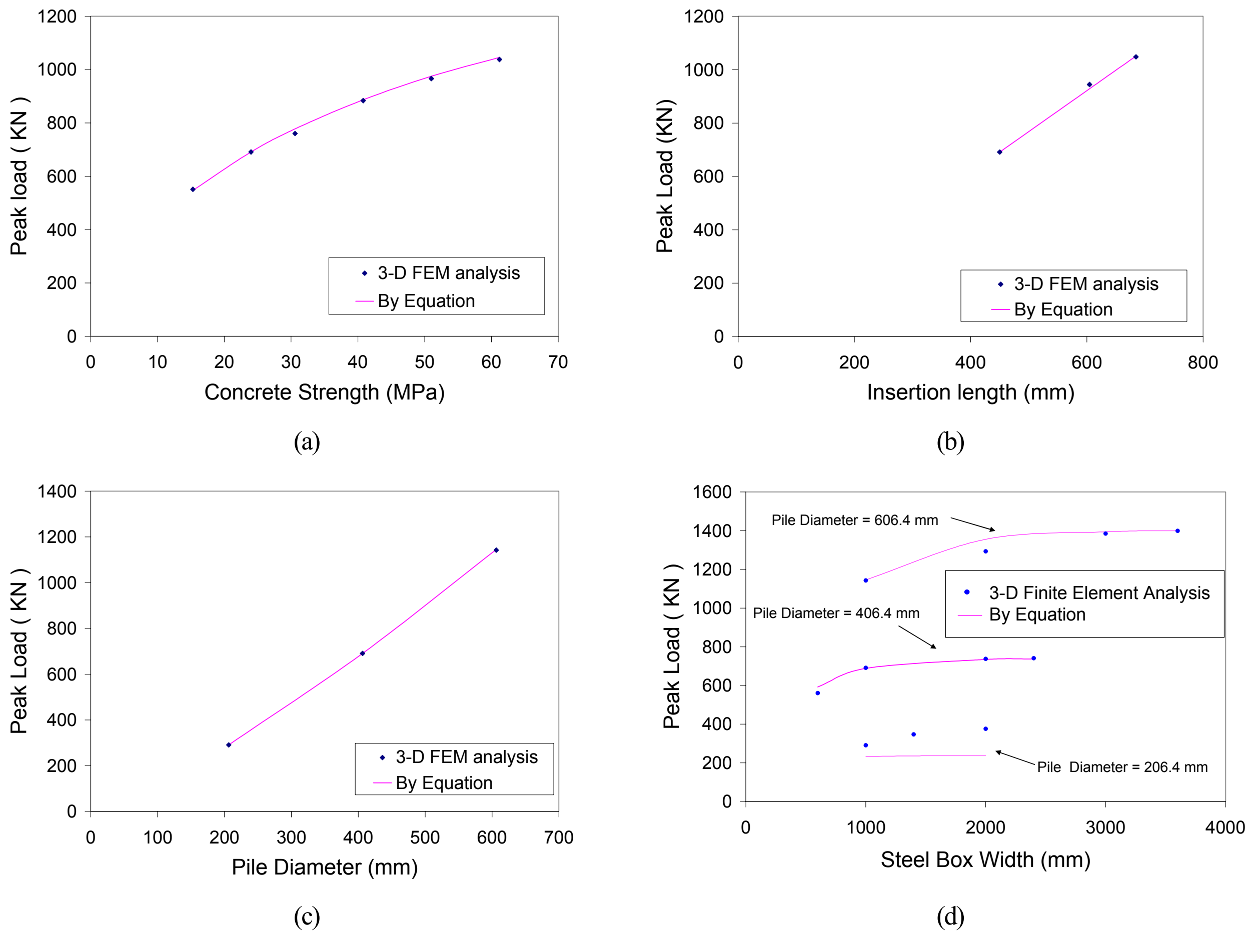

Fig 25 Comparison of results between 3D FEM analysis and Equation's result

Ultimate load capacity of the connection increases with the increase of the pile diameter. This increase is due to the increase of the resultant of concrete bearing stress distributed around the pile inside the steel box.

For different pile length outside the steel box failure of the connection takes place because of bending moment or shear force. For longer pile the failure takes place because of moment.

Tentatively a simple model to calculate the peak load for the case without yielding of steel pile. For the verification of the model further study with experiment is planned and the result will be reported in the future.

Acknowledgement: The authors are grateful to Mr. Kenji Emoto for his valuable help to understand the computer program used in this study and Dr Yasuhiko Sato for his valuable advise towards this study.

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(Received September 18, 2007)