A numerical approach for evaluating the stiffness of steel tube–R.C. beam composite joint

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1. Introduction

Composite connections between steel tubes and reinforced concrete are typically found at the foundation of composite columns and in pile supported wharves. The later are offshore structures commonly used as berthing platforms. A pile supported wharf typically consists of a reinforced concrete (R.C.), or a prestressed concrete, deck resting on steel tube piles.

Although the calculation of section forces and deformations of composite structures are usually based on the assumption that the connections between the steel tubes and the R.C. footing/deck are rigid, previous experimental work indicated that relative rotations took place between the ends of the steel tubes and the surrounding reinforced concrete. Experimental and numerical studies on the connections of concrete filled steel tube columns sufficiently embedded in RC footings showed that they had better inelastic performance and drift capacities compared to typical R.C. column/footing connections [1,2]. Similar studies on the base connection of composite columns embedded in RC footings were performed by Pecce and Rossi [3]. They concluded that the contribution of the fixed-end rotation due to the inelastic behaviour of the

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Abstract A numerical approach has been developed for the analysis of composite joints of steel tubes embedded in reinforced concrete. This kind of joint is typically found at the foundation of composite columns and in open pile supported wharves. The performance of such joints is thought to have a considerable effect on the overall behaviour and ductility of the structures containing them as indicated by previous experimental and analytical work. The developed approach was based on a two-stage two dimensional analysis to account for the three dimensional nature of the joint behaviour. The validity of the new approach was proven by applying it to previously experimentally tested composite joints. Good agreement was observed between the joint behaviour as produced by the numerical analysis using the new approach and the experimental measurements. Considerable saving in computer run time was also achieved compared to the case of using three dimensional analysis.

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materials around the column base represented approximately 50–60% of the total deformation of the column in the plastic field.

Yokota et al. [4–6] performed experimental tests on pile supported wharf models and indicated that relative rotations were evident between the ends of the steel piles and the surrounding reinforced concrete. Further analytical studies by El-Bakry et al. [7] on the models tested by Yokota et al. took into account the actual stiffness of the joints, as experimentally measured, and showed that this relative rotation was responsible for 36% and 46%, in average, of the total lateral displacements of the studied wharves at the first yield loads and the ultimate loads respectively.

Fig. 1 shows the details of the five wharf models (scale 1:4) previously experimentally tested by Yokota et al. Each of the models represented one row of piles supporting an R.C. beam which portrayed the R.C. deck of a pile supported wharf. Table 1 shows the parameters identifying the different five wharf models. These models were studied under increasing horizontal loads acting at the level of the R.C. beams to represent seismic forces in addition to constant vertical loads at the piles to represent gravitational loads. Fig. 2 shows the reinforcement details of model W4, as an example, which illustrates the joint detailing. The bottom reinforcement of the beam was welded to the steel piles through welded gusset plates. Concrete was cast to form the concrete beam around the ends of the piles and inside the topmost parts of them. This was the same detailing adopted in common practice in the construction of open pile supported wharves.

Fig. 3 shows the numerical model used in the previous study for the finite element analysis of the tested specimens [7]. Beam elements were used for modelling the horizontal R.C. beam and the vertical steel piles. Special beam elements defined by their moment-curvature relationship were used for modelling the parts of the piles embedded in the R.C. beam/base to account for the effect of the degrading joint stiffness. The behaviour of the joints, introduced in the numerical analysis, was based on the experimental measurements of the joint rotation during the experimental testing of the wharf models. Figs. 1–3 as well as Table 1 are reproduced here for their relevance to the current work.

The use of a special joint element was also adopted by Karayannis et al. [8] in studying the seismic performance of R.C. frames with joint stiffness degradation effect. The composite joint between a steel column and a composite beam was studied by Kattner and Crisinel [9] adopting linear constraint conditions in the finite element modelling to account for the linkage between the components of the joint. Several studies of similar connections were performed using two dimensional and three dimensional finite element analysis [10–12]. Three dimensional finite element modelling of the composite joint between concrete filled square tube column and an R.C. slab was studied by Ju et al. [13] looking mainly at the out of plane deformations that took place at the steel tube column.

As need arises for the construction of ductile structures that allow inelastic controlled deformations to take place [14,15], it is becoming important to develop a reliable method for calculating the deformations of composite structures under seismic loads. This is particularly important in the event of an earthquake that produces seismic forces exceeding the elastic limit of the structures.

In this paper, an approach has been developed to predict the degrading stiffness of the composite joint using numerical finite element analysis. The new approach was applied to the joints previously tested by Yokota et al. and a comparison was made between the joint stiffness obtained using the new approach and the stiffness obtained from the experimental measurements.

2. Nature of the problem

In design procedures of composite structures containing steel tubes embedded in reinforced concrete, rigid composite joints are normally assumed. Further analysis of the previously conducted tests revealed that the stiffness of such joints degraded due to the concentration of stresses in the concrete in the vicinity of the steel tubes. This led to local deformations that.

Figure 1  Geometry of test models [4–6].
were not accounted for in the structural analysis when rigid joints were assumed. This stress concentration resulted from the fact that the width of the R.C. beam was larger than the diameter of the steel tubes. Eventually, the locally high stresses in the concrete beam reached the crushing strength of the concrete leading to notable depreciation in the stiffness of the joints. Fig. 4 shows the connection between a steel pile and the R.C. beam after the experimental testing of one of the models by Yokota et al., W3. The gap that could be seen between the surface of the steel pile and the surrounding concrete depicted this type of local damage which is thought to be responsible for the deterioration of the joint stiffness.

### 3. The developed approach

Numerical studying of this problem should, ideally, be tackled considering three dimensional analysis of the joint. Therefore, nonlinear finite element analysis of a three dimensional model of the joint of the previously tested wharves was initially attempted. However, this kind of analysis proved to be time consuming and impractical for design purposes even when a relatively coarse mesh was used. Simple two dimensional modelling of the joint, merely in a vertical plane, would not represent its actual response as it is, fundamentally, a three dimensional problem. This three dimensional behaviour resulted from the combination of two factors. Firstly, as the joint was subjected to bending moments, main stresses were developed in the beam in its axial direction. The distribution of these stresses in the transverse direction, across the width of the beam, was not uniform. Secondly, the thrust of the pile, which had a circular cross section, against the concrete produced transverse splitting stresses in the concrete resulting in a reduction in its compressive strength in the axial direction. These two factors, typically unaccounted for in a simple two dimensional analysis, rendered such an analysis incapable of simulating the true behaviour of the joint.
To overcome these difficulties, the idea of a two-stage two dimensional analysis was conceived. The first stage of the analysis looked at the behaviour of the joint in the transverse direction in a horizontal plane. This would account for the effects of the stress concentration and the transverse tensile stresses on the behaviour of the joint. The second stage was a study of the joint in the vertical plane. Both stages encountered only two dimensional analyses which led to massive savings in the computer run times without compromising the reliability of the solution.

A schematic diagram illustrating this proposed approach is shown in Fig. 5. The study focused on the parts of the steel pile and the R.C. beam close to the joint as shown in Fig. 5a. The beam was divided into horizontal layers having equal thicknesses in the vertical direction. Each of the horizontal layers consisted of a concrete filled steel ring and a R.C. plate as shown in Fig. 5b. The behaviour of one such layer was studied under the effect of a horizontal load \( P \) pressing the steel ring against the concrete plate and the relationship between \( P \) and \( \delta \), the corresponding axial displacement, was established. Each of the horizontal layers was then replaced by an equivalent spring having the \( P-\delta \) relation as obtained from the horizontal layer analysis. The whole joint could then be reduced to the two dimensional model shown in Fig. 5c where the steel pile was replaced by beam elements and the concrete beam was replaced by a set of springs. A bending moment was applied to the end of the steel pile of this two dimensional model and a relationship between the applied bending moment, \( M \), and the corresponding angle of rotation, \( \theta \), was established. This relation could be incorporated in the frame analysis of the wharves as the properties of the joint elements representing the parts of the piles embedded in the R.C. beam, see Fig. 3.

The longitudinal reinforcement of the R.C. beam was ignored in the analysis of the joint. It was believed that the longitudinal reinforcement did not have a significant effect on the behaviour of the joint. This assumption was supported by the experimental results of the previously tested wharves. The moment–curvature relationships for the joints obtained from the previous experimental measurements did not show any significant correlation with the varying reinforcement ratio of the tested models. This could be attributed to the local buckling of rebars, at the compression side of the piles, which might have resulted in a reduction in their compressive resistance. On the other hand, rebars at the tension side of the piles might have lost part of their tensile forces due to loss of bond along parts of their lengths in the immediate vicinity of the steel piles. Also, local deformations of the pile wall at the connection with the longitudinal rebars could have reduced the effect of these rebars on the stiffness of the joint. Shrinkage bars, placed at both sides of the R.C. beam, were also ignored as their total area was generally small and their location was away from the piles. However, the beam lateral reinforcement, the stirrups, was accounted for in the first stage of the analysis of the joint, the horizontal layer, because of their confining effect and its significance on the biaxial response of the concrete.

4. Joint analysis and model verification

4.1. Finite element modelling

The proposed approach was applied to the joints of the wharf models previously studied by Yokota et al. and El-Bakry et al., see Fig. 1. The commercial finite element package SOLVIA was used for the nonlinear numerical analysis performed in this study. The part of the R.C. beam surrounding the steel pile was divided into five horizontal layers having equal thickness (53.5 mm each). Fig. 6a shows the geometry of a typical horizontal layer which consisted of a concrete filled steel ring and an R.C. plate as considered in the finite element modelling. Only the part of the layer in the compression side was considered in the analysis as the concrete in the tension side was thought to be ineffective in determining the behaviour of the layer under the effect of a load \( P \). At the compression side, the dimension of the layer in the axial direction was so determined that the minimum dimension of concrete equals to the pile diameter, 267.4 mm. This was assumed to include the main area of concrete where the uneven axial stress distribution took place. The dimension of the layer in the transverse direction was equal to the beam width, 500 mm.

Material properties were taken equal to the actual values used by Yokota et al. as obtained from experimental testing. The concrete compressive strength was taken equal to 37 N/
2. The yield stress of the deformed bars used for stirrups was 375 N/mm$^2$. The yield stress and tensile strength of the steel piles were 369 N/mm$^2$ and 462 N/mm$^2$ respectively.

4.2. Transverse layer joint analysis

The relative rotations that took place at the joints were merely due to the surplus deformations resulting from the stress concentration due to the difference in size between the pile and the beam. Therefore, not all the displacement resulting from the application of the load $P$, in the layer analysis, would contribute to the relative rotation of the joint. Part of this displacement was equivalent to the displacement that would typically take place if a uniform axial stress was applied to the same layer. The effect of this uniform axial stress, and consequently strain, was demonstrated in the form of curvature in the R.C. beam and was to be, typically, accounted for in the frame analysis of the wharf models. Consequently, the excess rotation that took place at the joint, and was not accounted for in the frame analysis, was due to the difference in displacement between the case of a concrete filled steel ring pressing against the concrete layer and a case of concrete layer subjected to uniform axial stress. Fig. 6 shows these two cases as considered for the current joint analysis. The case of the steel ring pressing against the concrete is shown in Fig. 6a and would result in the total displacement $\delta_t$. Fig. 6b shows the uniformly loaded counterpart layer of concrete which was used to calculate the corresponding displacement $\delta_c$. The finite element mesh used for the analysis of the transverse layer is shown in Fig. 7. The net displacement, $\delta_n$, which would effectively cause the relative joint rotation, was then calculated as:

$$\delta_n = \delta_t - \delta_c$$

The results of this layer analysis are shown in Fig. 8. The two curves of $\delta_t$ and $\delta_c$ were obtained from analysing the two models shown in Fig. 6 while the curve of $\delta_n$ was obtained using Eq. (1). The relationship between the horizontal load, $P$, and the corresponding net displacement, $\delta_n$, was considered as the mechanical properties of the spring substituting the horizontal concrete layer.

As the post crushing strength of the confined concrete was ignored, a sudden drop in the $P$–$\delta_t$ relation of the concrete layer took place and numerical problems prevented the analysis from proceeding well into the descending branch of the curve. However, the considered idealised ($P$–$\delta_n$) relation of the equivalent spring was assumed to have a horizontal plateau past the peak load.

4.3. Vertical plane joint analysis

In the second stage of the analysis, the joint model was reduced to a two dimensional model in a vertical plane, similar to the one shown in Fig. 5c. The layers of concrete were replaced by the equivalent springs having the force–displacement relation shown in Fig. 8 and the steel pile was modelled using beam elements. The stiffness of the joint as described by moment–rotation relationship, as obtained from the analysis of this equivalent model, is shown in Fig. 9. The figure also shows a comparison with the experimentally measured joint rotations for the previously tested wharf models (W1–W5). Reasonable agreement could be found between the numerical and the experimental results particularly for lower bending
moments. However, it could be seen that the joint rotations were underestimated at higher bending moments which could be attributed to the post crushing behaviour of concrete which was not accurately accounted for in the concrete material model of the transverse layer analysis. This would have resulted in a gradual loss of stiffness past the peak load, instead of the assumed horizontal plateau, of the equivalent springs replacing the concrete horizontal layers.

5. Full wharf model analysis

Furthermore, nonlinear analysis of finite element models, representing the previously studied five wharf models, was conducted. The geometry and material properties of the finite element models were similar to those used by El-Bakry et al., see Fig. 3. However, the properties of the joint elements representing the parts of the piles embedded in the R.C. beams were obtained from the numerical analysis of the joint according to the developed approach and as shown in Fig. 9. The models were analysed under the effect of horizontal static loading acting at the level of the R.C. beam and the corresponding horizontal displacements were calculated.

The results of this current analysis are shown in Figs. 10–14 together with the results obtained from the experimental testing and from the previous numerical analysis performed using experimentally obtained joint stiffness. The results of finite element analysis assuming rigid joints are also shown for comparison. It could be seen from these figures that using the numerical approach in determining the joint stiffness produced good results in calculating the horizontal displacements of the models. This showed more clearly in the elastic, and early ultimate, stages of the considered models.

As the horizontal loads were increased approaching the ultimate levels, the model behaviour based on the developed approach showed good agreement with the previous analytical results based on experimentally obtained joint stiffness. This proves that the developed approach is reliable in evaluating the composite joint stiffness. On the other hand, comparing the new set of curves with the experimental results showed
good agreement for models W1, W2 and W3 while for the other two wharf models, W4 and W5, with piles having a thinner wall, the calculated horizontal deformations underestimated the experimentally measured ones. However, the analytical results, generally, underestimated the horizontal displacements. This was attributed to the local buckling of the steel piles which was not accounted for in the finite element frame analysis. However, comparing the results obtained using the developed approach and those obtained using the experimentally measured joint stiffness, the developed approach proved to be reasonably effective in predicting the joint behaviour as far as the horizontal displacements of the wharves were concerned.

It is worth mentioning that the experimental tests were carried out on approximately 1:4 scale specimens. This might have had an effect on the experimental behaviour of the joints as the concrete response is scale sensitive.

6. Conclusions

The following conclusions could be drawn from the work presented in this paper:

1. An analytical approach has been developed for calculating the degrading stiffness of the composite joint of steel tubes embedded in reinforced concrete beams. This approach was based on a two-stage two dimensional finite element analysis and proved to be effective in substantially reducing the extensive computer CPU time normally required for a typical three dimensional analysis of such a joint.

2. The developed approach, based on two dimensional numerical analyses, proved to be successful in accounting for the three dimensional behaviour of the joint. This was verified by comparing the joint behaviour resulting from the finite element analysis based on the developed approach with previously experimentally measured joint behaviour.

3. The variation between the numerically calculated and the experimentally measured joint stiffness could be partially attributed to the post crushing behaviour of concrete which was not accurately modelled in the finite element analysis.

4. Comparing the horizontal displacements obtained from analysing wharf models subjected to horizontal loading using the developed approach with previous experimental and analytical results showed good agreement especially in the elastic and early plastic range.

5. The finite element analysis of wharf models with thin steel pile walls slightly underestimated the horizontal displacement compared with the experimental measurements especially at higher loads. This could be attributed to the local buckling of the steel tube piles which was not accounted for in the current study.

6. More elaborate finite element modelling is recommended to account for the post crushing behaviour of concrete and the local buckling of steel tubes.

References