論文 Finite Element Analysis of Steel Girder-Concrete Pier Rigid Connection

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ABSTRACT: To analytically simulate the behavior of the structure consisting of rigid connection between steel girder and concrete pier, finite element analysis is applied. In the paper, finite element modeling is presented. The reliability of proposed model with application of smear-crack concept for reinforced concrete is checked by comparing to the experimental results.
KEYWORDS: composite, reinforced concrete, steel, connection, finite element analysis

1. INTRODUCTION

As it is considered to be advantageous in construction, for some steel–concrete composite bridges, the fully embedded connection between steel girder and reinforced concrete pier forming rigid connection is recently adopted. Prototype specimens have been tested to confirm the performance of structure before the real implementation[1]. However, it is costly to conduct the test, and the result can represent the behavior of only individual type of connection tested. Therefore, the reliable analytical methodology is necessary to facilitate the safe and economical design. In this paper, finite element method is used to simulate the mechanical behavior of such a connection. A widely-used material model for reinforced concrete, smear-crack model, are also described and checked for its applicability. Verification of the proposed method is made by comparing with the results obtained from the experiments previously conducted by Japan Highway Corporation and Construction companies[1].

2. SPECIFICATIONS OF PROTOTYPE SPECIMEN

Prototype specimen was made in an experiment which was designed based on the rather safe criterion as the accurate behavior still cannot be predicted analytically. Materials and specification used in constructing specimens are as shown in Table1 and Fig.1,

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Table1 Properties of materials used

Material Properties	Concrete	Reinforcing Bar	Steel Plate
Modulus of Elasticity(MPa)	22,978	187,866	208,282
Compressive Strength(MPa)	31.03	-	-
Yield Strength(Mpa)	-	373.8	297.2
Splitting Strength(MPa)	2.39	-	-

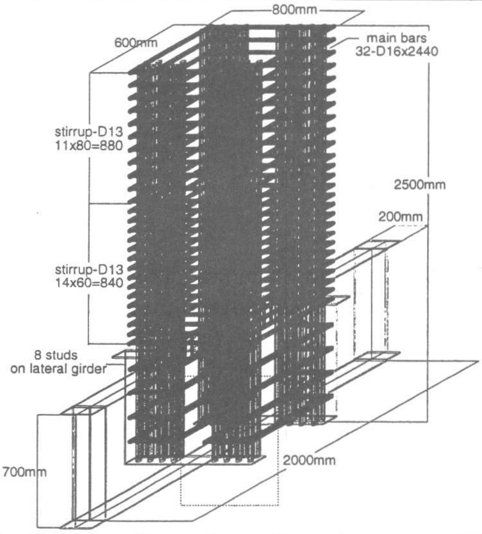

Fig.1 Design dimensions of specimen type-1B

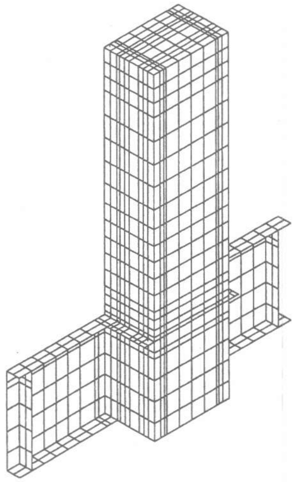

Fig. 2 Finite element modeling of specimen

3. FINITE ELEMENT MESH MODELING

A finite element package provided by Marc Analysis Research Corporation was utilized in computation along with the pre-and post-processing programs, Mentat. Nonlinear finite element analysis was conducted taking into account the non-linearity of concrete, reinforcing bar and steel. Concrete was physically modeled by a 8-node hexagonal element. 2-node truss element was used for all reinforcing bars including longitudinal ones and the stirrups. To model the main and lateral steel girders, 4-node thick shell was utilized. For studs, 2-node beam element with stiffness in transverse direction was applied to simulate the mechanical behavior. The full mesh model of specimen type 1B is shown in Fig.2. For boundary conditions, the advantage of symmetry was taken in the analysis. A half model was generated with fixed displacements and rotation boundary conditions applied on its half plane. The fixed translation in all directions was applied at both supports in addition to rotations which were held firmly in x and z directions at the support locations. For the mechanical boundary condition on the top of concrete pier, constant downward pressure of magnitude 0.49MPa was continuously imposed from the beginning throughout loading steps, as identical to that in the experiment. The horizontal load was monotonically applied at 50 kN for each increment at the point 200 mm below the top of pier.

4. MATERIAL BEHAVIORS MODELING

4.1 REINFORCED CONCRETE

The stress-strain relationship of concrete under uniaxial compression was derived based on compression test data as shown in Fig.3. Along with the empirical uniaxial compressive behavior of concrete, it was assumed in the analysis that under multi-axial stress state, concrete would behave as work-hardening plastic material of which yield surface could be described by the model introduced by Buyukozturk[2].

Under tensile stress, plane concrete behavior can be categorized into 2 successive phases, namely, before reaching tensile strength, and beyond the peak tensile strength. Before the cracks initiated in concrete, the concrete was assumed to behave elastically with the same modulus of elasticity as in elastic compression ($E_{s(tension)}$ = 22,978 MPa). However after reaching the peak tensile strength (f_t = 2.39 MPa, obtained from tensile splitting tests), cracks were generated. This caused concrete to behave in, totally, different way comparing to the isotropic material behavior assumed in the earlier stage. Concrete started to exhibit as it was anisotropic material with no resistance to any forces in the direction normal to the crack plane. Nevertheless, it still can withstand the shear force exerting on the plane of crack with gradually reducing shear stiffness. This is mainly contributed by the aggregate interlock and dowel action. Bangash[3] has proposed the linear relationship between shear resistance of cracked concrete and the tensile strain normal to the cracked plane. It was adopted here as;

$$\tau^* = \beta' G \gamma^* \tag{1}$$

where; G is the shear modulus of uncracked concrete, β' is the interlocking factor = $1-(\varepsilon_t/0.005)^{K1}$, ε_t is the tensile strain normal to the crack plane, K1 ranges from 0.3-1. The shear retention factor β' was adopted and multiplied by shear modulus of uncracked concrete, G, for the new shear modulus ($G_{new} = \beta' G$). K1 was assumed to be equal to 1.

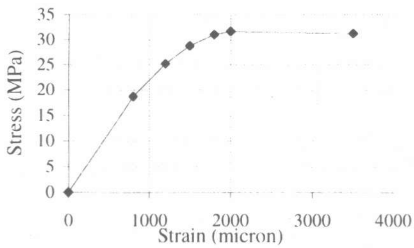

Fig.3 Experimental stress-strain relation of concrete under compressive stress

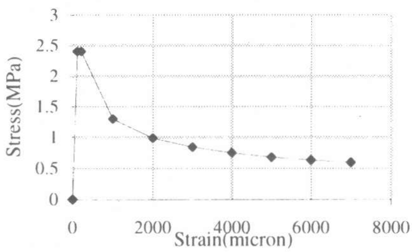

Fig.4 Constitutive model for concrete in tension

In reinforced concrete, the concrete is, typically, not standing alone resisting multi-axial stresses, but with reinforcing steel. The presence of bar helps enhance the concrete behavior especially under tensile stress. Regarding the interface between concrete and reinforcement, idealization for reinforced concrete elements can be roughly classified into two categories. One is the discrete idealization, in which concrete and reinforcing bars are separately discretized into different elements. The other is the smeared idealization, in which concrete and reinforcing bars are discretized into element with the same geometrical boundaries and the effects of reinforcing bars are averaged within the pertaining element. In this analysis, the latter was adopted for characterizing the stress-strain relationship of reinforced concrete, though there were still some disadvantages incorporated. In the discrete method, concrete and reinforcing bar element need a kind of link element to connect. The bond stress-slip model of reinforcement in concrete is needed for describing the force-displacement behavior of this link element. In the finite element analysis, though this type of idealization gives more physical meaning and probably more accurate results in the case that discontinuity exists in the structure, it is rather difficult to be implemented than the smear type.

The smear crack concept, in which the occurrence of distributed cracks is assumed, is applied to this analytical work. The concrete which, normally, can no longer resist any tensile stress after reaching peak tensile strength is modeled as a material of gradually decreased stiffness. In the smear-cracked model, even though the concrete on the crack plane is not able to transfer any more tensile force, the cracked concrete still can further resist tensile force contributed by a reinforcing bar. Thus, within a smear-cracked concrete element, the average tensional resisting capability is applied to expressed the overall behavior of the element. It should be noted that, not only the concrete element but also the reinforcing steel shows an average behavior based on smear-crack concept. Many reseachers have used the smear-crack concept to analyze concrete structure, but somehow they have neglected to extend this concept to modify the stress-strain relationship of the reinforcing bars crossing the cracked concrete. This may eventually leads to the over-stiff response of overall structure in the case that reinforcing bar yields at some sections. In this work, the tension stiffening model proposed by Okamura[4] is adopted. In this model, the cracks are considered not to appear as soon as the stress has attained its cracking level, but the principal tensile strain reaches a limit strain. This limit strain is usually between 0.01% and 0.03%, and is larger than the corresponding stress on the fracture envelope. As a result, there is a certain amount of plastic deformation taking place. This has been expressed in the present model by assigning to the tensile limit strain that is twice as much as the tensile strain corresponding to the tensile strength of the concrete. The model is shown in Fig.4.

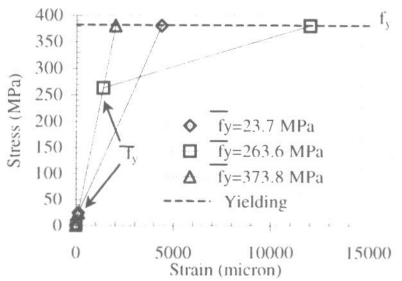

Fig.5 Constitutive law for reinforcing bar

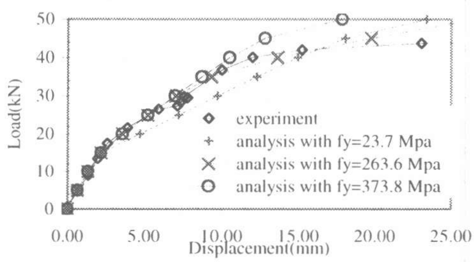

Fig.6 Load-Displacement Relationship

For the constitutive relation of reinforcing bar crossing the crack, the one proposed by Shin[4], which was developed by taking into account the factors influential to the post-yielding constitutive laws, was used. In his work, the parametric study was conducted for 140 cases. The results showed that the average stress and average strain could be well related in a bilinear fashion having a clear offset point for initiation of strain hardening (yield stress = $\overline{f_y}$ as in eq.2). Beyond yielding point ($\overline{f_y}$), the strain hardening rate held constant at Esh.

$$Esh = 100(f_y - \overline{f_y})\, K_p\, K_y\, K_h\, K_a\, K_c\, K_k \quad (2)$$

Where; $\overline{E}sh$ = strain hardening rate in bilinear stress-strain relationship of reinforcing bar
$\overline{f}_y \geq 0.5K_{yo}K_{ko}fy$, $K_p = px^{0.5px}$, $K_y = (400/fy)^{0.1(px/py)cosec\theta}$, $K_h = (px/py)^{0.067}$,
$K_a = cosec\theta^{0.2}$, $K_c = (30/fc')^{0.25}$, $K_{k0} = 1$ for deformed bar. fy =yield strength(MPa),
$K_{y0} = (0.1pxfy/fc')^{0.5} \leq 1$, px,py = reinforcement ratio in each direction,
fc':compressive strength of concrete MPa.

Before the first yielding, it was assumed that the bar remained elastic with modulus of elasticity equaled to its actual value, while the post-yielding constitutive relationship can be determined by using eq.2, as shown in Fig.5 After the stress reaches actual tensile strength (f_y), the bar is assumed to behave like a perfectly plastic material. For the studied case, Esh was found to be 82,312 kN, where $\overline{f}_y = 23.73$ kN/mm^2.

4.2 STEEL PLATE

For the steel plate, it was assumed to behave elastic-perfectly plastic. von Mises criteria was used to express yield surface of this material. The interface between steel plate and concrete was assumed to be perfectly bonded in order to simplify the analysis and to reduce the calculation time.

5. ANALYTICAL RESULTS AND ITS VERIFICATION

After applying the material constitutive laws to the three-dimensional elements generated in finite element program, Marc, the static non-linear analysis was performed. The results obtained are a load-displacement relation at loading point, the relationship between load and tensile stress in reinforcing bar located on the outer layer of tensional side, and the relationship between load and maximum and minimum principal strains on steel girder. These results are as shown in Figs.6, 7, and 8.

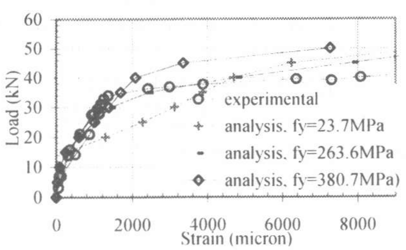

Fig.7 Load-bar strain relationship

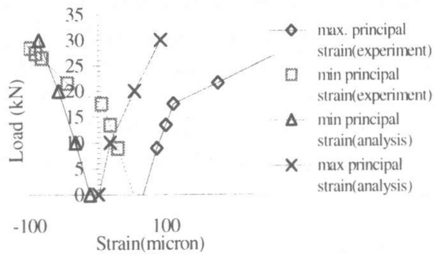

Fig.8 Load-web's center principal strains

With the proposed analytical model, it is found that, the structure responds to applied load in a less stiff manner than in an experimental result as in Fig.6. As well, Fig.7 shows that the steel strain increases extensively after the load where the crack has extended in concrete (around 25 kN). The reason for this less-stiff manner of structure is expected to be due to the effect of modified constitutive law of reinforcing bar. Therefore, this factor has been rechecked by performing analysis of two more comparative cases. For the case1, the constitutive relation of reinforcing bar is assumed to be elastic-perfectly plastic with a yield stress of same magnitude as in the experiment (fy=373.8 MPa). In the other case, case2, the constitutive law was assumed to posses two yielding points, where the first yielding point was assumed to be $\bar{f}_y$ = 263.6 MPa and the second was just identical to yield stress of actual reinforcing bar (f_y) in Fig.5. The same analytical procedure was conducted and the results of these two cases were shown in Fig.6 and Fig.7. It can be clearly seen that with using reinforcing bar model proposed by Shin, the structure behaves less stiff compared to the test result. On the other hand if the actual elastic-perfectly plastic model with actual yield point, case1, is applied the structure behaves in a stiffer manner than the real one. However, if the constitutive model is assumed to have two yield points, case 2, with $\bar{f}_y$ = 263.6 MPa, the analytical prediction showed quite comparable result to the experimental data both in elastic and inelastic ranges. It can be concluded that the constitutive relation proposed by Shin is not general and the more accurate constitutive law is still needed. As for the comparison, between principal strains at the middle of main girder's web obtained from the analysis (case2), and that of the experiment, the analytical results are still deviated from the maximum and the minimum principal strains compared to experimental results. This might be due to the inaccurate assumption in the analysis that the plate and concrete element are always rigidly fixed each other. Implement of a more complicate model for the interface between steel plate and concrete may provide improvement to the accuracy of analysis.

6. CONCLUSIONS

1. Mechanical behavior of steel girder-concrete pier rigid connection specimen could be closely simulated with the proposed analytical model as can be seen in the comparisons between experimental and analytical results.
2. Constitutive law of the reinforcing bar with two yield points gives more accurate results in analysis than that with only one yield point. It is obvious that when the post-yielding constitutive law is modified, the mechanical behavior has been noticeably changed. However, there is still a necessity for the more general and accurate constitutive equation, since the one proposed so far by Shin has a limit in the application.
3. The model of the interface between concrete and steel plate is needed to be improved. The perfectly bonded assumptions might be one potential cause of an inaccuracy, such as that can be seen in the load-web's center principal strains relationships, Fig.8.
4. Some other influential factors that should be considered further are, the anchoring of reinforcing bar, and the effect of large cracks above the connection. These factors can be taken into account if the discrete reinforced concrete model is applied.

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