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Investigation of semi-rigid bolted beam connections on prefabricated frame joints

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Abstract. Bolted connections are used commonly in the precast reinforced concrete structures. In such structures, to perform structural analysis, behaviour of connections must be determined. In this study, elastic rotation stiffness of semi-rigid bolted beam connections, applied in industrial precast structures, are determined by finite element methods. The results obtained from numerical solutions are compared with an experimental study carried out for the same connections. Furthermore, stress distributions of the connection zone are determined and a reinforcement scheme is proposed. Thus, a more appropriate reinforcement arrangement for the connection zone is enabled. The connection joint of the prefabricated frame is described as rigid, hinged or elastic, and a static analysis of the frame system is performed for each case. Values of bending moments and displacements obtained from the three solutions are compared and the effects of elastic connection are discussed.

Key words: prefabricated reinforced concrete; bolted connection; semi-rigid connection; elastic connection; elastic rotation stiffness.

1. Introduction

In industrial precast structures, one or more additional spans to an existing structure may be required. In this study, we deal with problems faced in the formation of column and foundations of a new structure in applications. If such proldems are foreseen early enough, a special precast element that does not require a new column and new foundation may be used at the intersection of the existing structure and the additional part (Figs. 1 and 2). For this reason, a bracket supporting the special precast element is constructed and holes for the bolted connections are drilled on the enlarged side column of the existing structures. The special precast element is connected to the bracket on the column of the existing structure by using a high strength bolt. High strength bolt serves as a tension bolt to resist the bending moment that develops at the top of the column and another fixing bolt is also used at the compression zone for the stability of the connection. In addition, an elastomer support controlling compression surface on the bracket is settled on the bracket bearing the special precast element (Figs. 1 and 2).

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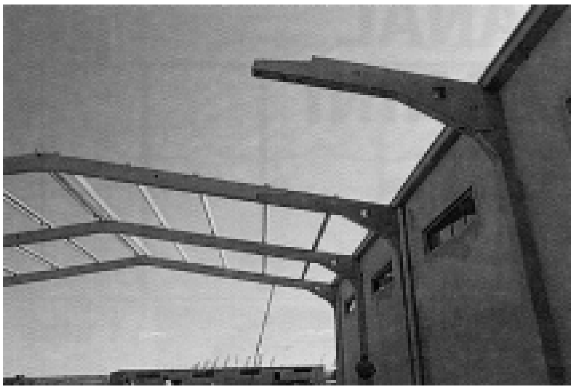

Fig. 1 View of structure being enlarged by a bolted beam connection

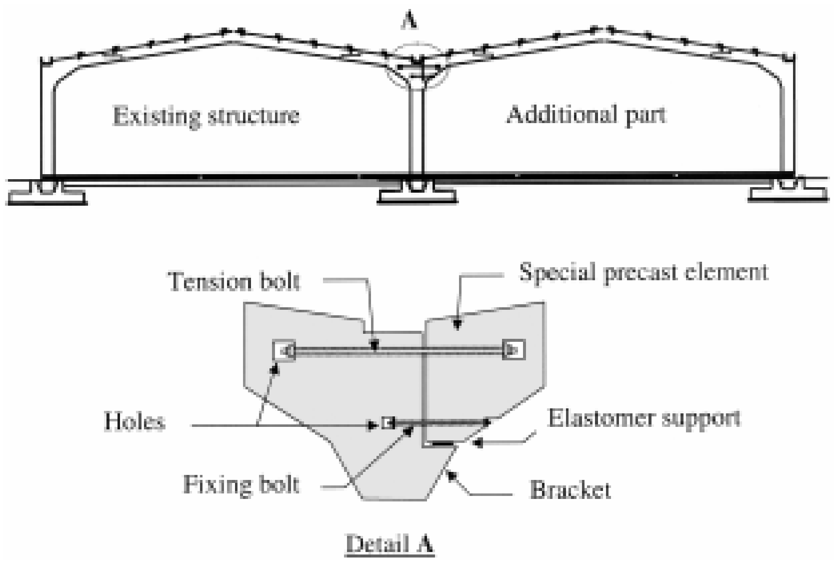

Fig. 2 Structure enlarged by a bolted beam connection and Detail A

2. Determination of the elastic rotation stiffness

The special precast element is connected to the rigid column-beam connection of the existing structure with a high strength bolt. Thus, an elastic connection at the rigid joint is constituted. In order to analyse the new system, the value of the elastic rotation stiffness must be known. Therefore, an initial analysis model is developed by taking and suitably supporting a section around the connection. Loading which represents behaviour of the connection in the system is performed on this initial analysis model. After loading, a separation forms in the tension zone of the connection section and a contact forms at the compression zone of the connection section. Since length of the compression zone is not initially known, it is determined using an iteration method. For this reason, fictitious double hinged bar elements are placed along the edge in the model (Fig. 3) and the initial analysis model is solved under service loads. Then, the fictitious bar elements bearing

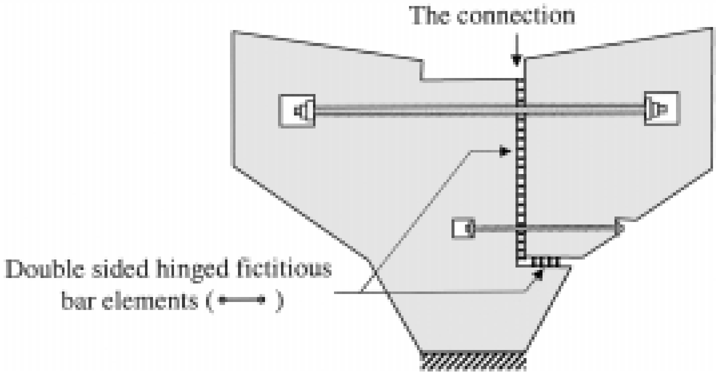

Fig. 3 Initial analysis model

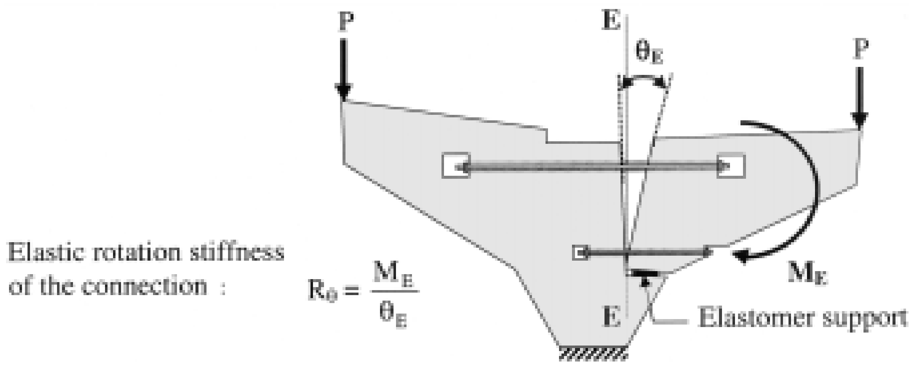

Fig. 4 Elastic connection to rigid joint and θ_E

tensile force are removed from the system and the system is analysed again with the remaining fictitious bar elements. This process is repeated until there is no fictitious bar element bearing tensile force. As a result, analysis model representing the connection is obtained (Irtem, Çolak and Türker 1999, Türker 1998, Çolak 1996, Aydoğan and Aköz 1995).

This analysis model is resolved under increased loads. For each load increment value, the relative rotation (θ_E) and the bending moment (M_E) in the connection section (***E-E***) are calculated, and then the elastic rotation stiffness value of the connection ($R_\theta = M_E/\theta_E$) is determined (Fig. 4).

3. Assumptions and method of analysis

In our calculations, it is assumed that first-order theory is valid and the stress-strain relation of the material is linear-elastic. The system is analysed for plane stress case by using the finite elements method (Çaklroğlu, Ender and Özmen 1992, Zienkiewicz 1983). In the analysis model, reinforced concrete elements are defined by plate elements and steel bolts and fictitious bar elements are defined by double-sided hinged bar elements. It is assumed that σ_x, σ_y, τ_{xy} stresses of plate elements do not change in the direction of thickness. In this case, σ_z, τ_{xz}, and τ_{yz} stresses are zero. Rectangular and bar plane finite elements used in the analysis model and edge displacements are shown in Fig. 5.

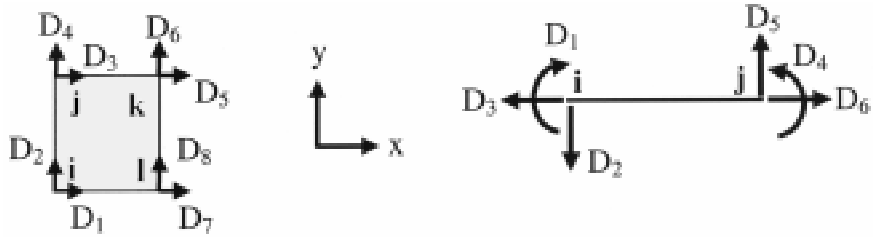

Fig. 5 Rectangular and bar plane finite elements and their edge displacements

4. Numerical example

4.1 Determination of the analysis model

As an example, a typical industrial structure applied in practice is selected. The structure has two spans of 20 m and 6 m height. Concrete strength of prefabricated reinforced concrete elements in the structure is 25 N/mm^2 and its elasticity module is 2.5×10^4 N/mm^2. In connection of the structure, there are tension bolt 40 mm in diameter, fixing bolt 25 mm in diameter (high strength steel; $E = 2 \times 10^5$ N/mm^2, $\sigma_{yield} = 949$ N/mm^2, $\sigma_{rapture} = 1045$ N/mm^2), and elastomer support $10 \times 150 \times 150$ mm in dimensions ($E = 3 \times 10^2$ N/mm^2). A connection zone with a determined dimension was separated from the prefabricated frame and fix-supported from bottom section (Fig. 6). A load P was applied at the edges of the beams. The prefabricated reinforced concrete elements are represented by rectangular plate finite elements. Steel bolts and elastomer support are represented by plane bar elements. The reinforced concrete elements were divided into 1152 rectangular plate finite elements. Twenty fictitious double-sided hinged bar elements along the vertical connection edge

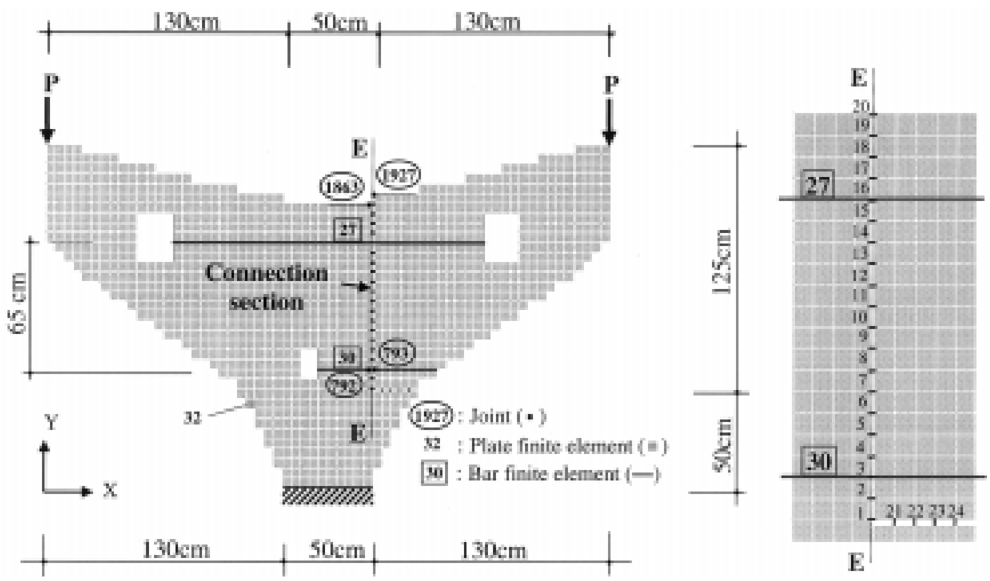

Fig. 6 Initial analysis model of the system and the connection section

with 5 cm intervals and four fictitious double-sided hinged bar elements (elements numbered with 21, 22, 23, 24), along the horizontal connection edge where the steel reinforced elastomer support exists, were defined. In addition, bar elements were defined for steel bolts. Thus, an initial analysis model was developed (Türker 1998) (Fig. 6).

The initial analysis model was solved under service loads using SAP 90 software (Wilson and Habibullah 1992). In the initial solution, nine fictitious bar elements bearing tensile force were observed. These fictitious bar elements (elements numbered with 12, 13, 14..., 20) were removed from the system and the system was solved again with the remaining fictitious bar elements (Fig. 7a). In the second solution, four fictitious bar elements bearing tensile force were modelled. These fictitious bar elements (elements numbered with 11, 10, 9, 8) were also removed from the system

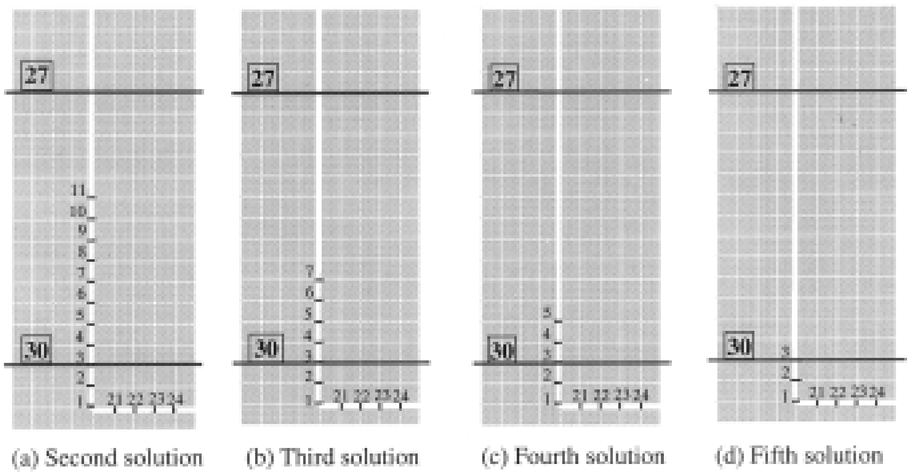

Fig. 7 The connection sections and fictitious bar elements

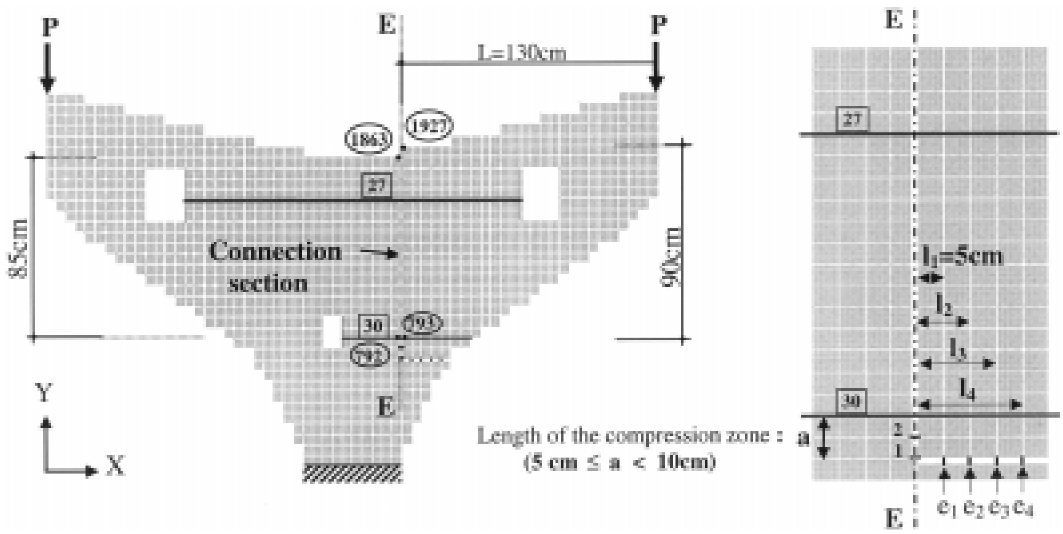

Fig. 8 Analysis model of the system and the connection section

and the system was solved again with the remaining fictitious bar elements (Fig. 7b). In this way, in the third and fourth solutions, two fictitious bar elements bearing tensile force and in the fifth solution, a single fictitious bar element bearing tensile force were removed from the system (Fig. 7). In the sixth solution, fictitious bar elements bearing tensile force were not observed any more. As a result, the length of the compression zone in the connection section was found to be 5-10 cm (Fig. 8) (Türker 1998). Thus, the required analysis model was obtained to calculate the elastic rotation stiffness (Fig. 8).

4.2 Calculation of the elastic rotation stiffness of connection

In order to calculate the elastic rotation stiffness R_θ the relationship between bending moment M and rotation θ in the connection section should be determined prior to the calculation. For this reason, the system (Fig. 8) was solved under values of increased P load, from 20 kN to 260 kN (approximately service loads) (Türker 1998). For each solution, the bending moment M_E and elastic rotation angel θ_E of the connection section were calculated using Eq. (1), Eq. (2), respectively and were given in Table 1.

$$M_E = P.L - (e_1 .\, l_1 + e_2 .\, l_2 + e_3 .\, l_3 + e_4 .\, l_4) \tag{1}$$

$$\tan(\theta_E) = \frac{\delta_{1863} - \delta_{792}}{85} + \frac{\delta_{1927} - \delta_{793}}{90} \tag{2}$$

Where e_1, e_2, e_3, e_4 are axial compression forces in bar elements representing the elastomer support and δ is linear displacement in the direction of the X axis.

The deformed shapes of system and elastic rotation angle θ_E under service loads are given in Fig. 9. It is seen that the M_E-θ_E graphic, drawn by values of M_E and θ_E can be accepted as a linear (Fig. 10). By using this graphic, elastic rotation stiffness R_θ is found 64655 (kNm/rad) by means of Eq. (3).

$$\boldsymbol{R_\theta} = \frac{\sum_{i=1}^{n} \frac{(M_E)_i}{(\theta_E)_i}}{\boldsymbol{n}} = \frac{840510}{13} = \mathbf{64655}\ \text{[kNm/rad]}. \tag{3}$$

Table 1 Solution results

Solution No	P (kN)	M_E (kNm)	δ_{1863} (cm)	δ_{792} (cm)	δ_{1927} (cm)	δ_{793} (cm)	θ_E (rad)
1	20	23.167	1.126E-03	1.017E-04	3.183E-02	6.668E-04	3.583E-04
2	40	46.335	2.253E-03	2.034E-04	6.366E-02	1.334E-03	7.166E-04
3	60	69.502	3.379E-03	3.051E-04	9.549E-02	2.001E-03	1.075E-03
4	80	92.671	4.505E-03	4.068E-04	1.273E-01	2.667E-03	1.433E-03
5	100	115.837	5.631E-03	5.085E-04	1.592E-01	3.334E-03	1.792E-03
6	120	139.004	6.758E-03	6.102E-04	1.910E-01	4.001E-03	2.150E-03
7	140	162.172	7.884E-03	7.119E-04	2.228E-01	4.668E-03	2.508E-03
8	160	185.337	9.010E-03	8.136E-04	2.547E-01	5.335E-03	2.867E-03
9	180	208.507	1.014E-02	9.153E-04	2.865E-01	6.002E-03	3.225E-03
10	200	231.673	1.126E-02	1.017E-03	3.183E-01	6.668E-03	3.583E-03
11	220	254.841	1.239E-02	1.119E-03	3.501E-01	7.335E-03	3.941E-03
12	240	278.049	1.352E-02	1.220E-03	3.820E-01	8.002E-03	4.300E-03
13	260	301.174	1.464E-02	1.322E-03	4.138E-01	8.669E-03	4.658E-03

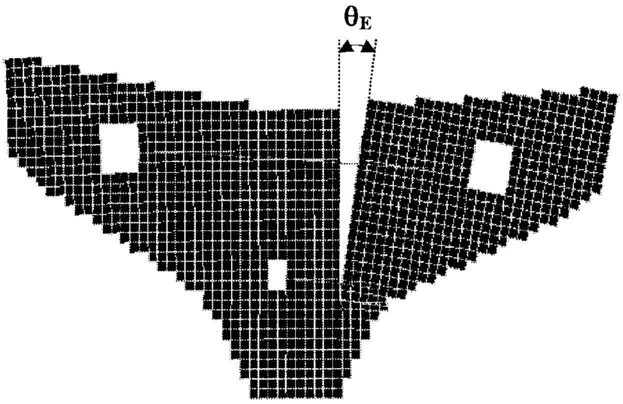

Fig. 9 Deformed shape of the system and θ_E

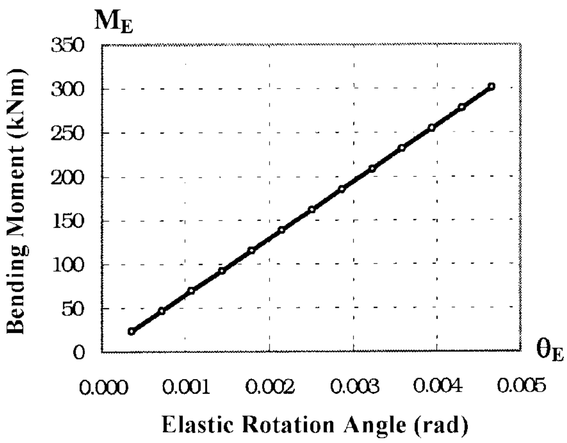

Fig. 10 M_E-θ_E Graphic

Where ***n*** is the solution number.

4.3 Determination of effect of the elastic connection

Three separate solutions of two spanned prefabricated reinforced concrete frame system were made under service loads (q=12.24 kN/m) to determine the effects of elastic connection on displacements and internal forces (Fig. 11). The connection was assumed to be rigid ($R_\theta = \infty$) in the first solution, hinged (R_θ=0) in the second solution, and elastic (R_θ=64655 kNm/rad) in the third solution. Bending moments and critical displacements obtained from the three solutions of the system are given in Table 2.

In the elastic connection solution, the value of the bending moment in the connection section (M_{CD}) is found to be ≈13% less than that of the rigid solution value. However, the values of the bending moment in some joints have increased ≈4.0%, in some supports have increased ≈14% and the CD beam's span moment value has increased ≈10% (see Table 2). From Table 2, the values of some critical displacement obtained from elastic connection solution were found to be about ≈13%

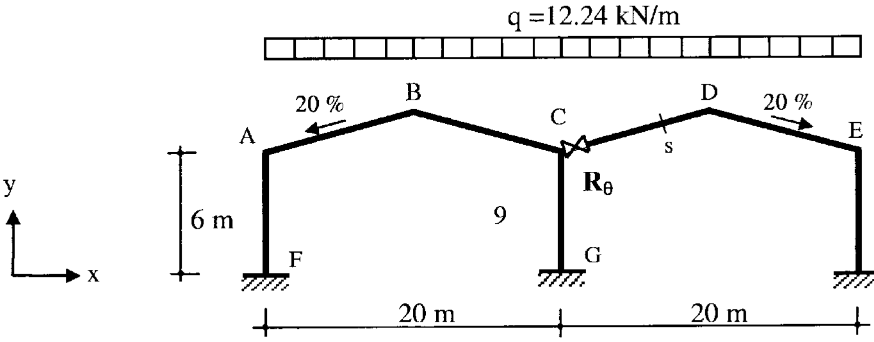

Fig. 11 Features and loading of two spanned prefabricated reinforced concrete frame system

Table 2 Bending moments and critical displacements of the system

Solutions	Bending moments (kNm)					Displacements				
R_θ (kNm/rad)	M_{CD}	M_{ED}	M_{FA}	M_{CG}	M_s	δ_{Ax} (cm)	δ_{By} (cm)	δ_{Cx} (cm)	δ_{Dy} (cm)	δ_C (rad)
∞	−321.3	−297.3	269.6	0.0	126.3	−2.29	−5.92	0.00	−5.92	0.00
0	0.0	−398.0	433.1	139.7	251.6	−4.66	−6.10	−2.33	−11.90	24.32E-3
64655	−279.6	−310.3	306.6	18.1	139.4	−2.59	−5.95	−0.30	−6.70	4.33E-3

more than those of the rigid solution (in Fig. 11. δ_{Ax} and δ_{Dy}). At the hinged connection solution, because of zero bending moment at the connection section, the values of bending moment at some other joints are found to be ≈28% more than those of the elastic connection solution and bending moments at some support joints are found to be ≈41% more than those of the elastic connection solution. Furthermore, high bending moment values have also occurred at the middle column. δ_{Dy} displacement obtained from the hinged connection solution is found to be ≈78% more than that of the elastic connection solution (see Table 2).

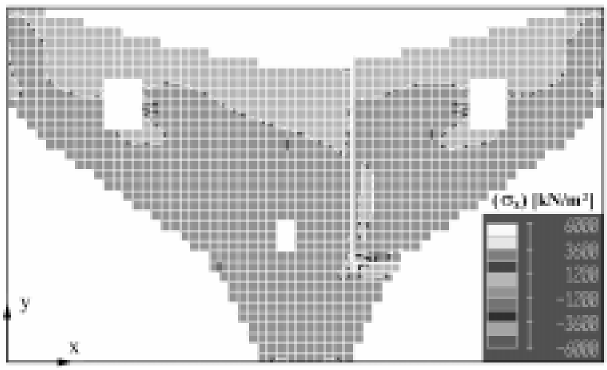

Fig. 12 σ_x normal stress diagram

4.4 Stress distributions in the connection zone

Normal and shear stress distributions were obtained for more suitable reinforcement placement in the connection zone of a prefabricated reinforced concrete frame. Stress distributions were obtained from solution under service loads. Stress values in the diagrams change while the load values acting

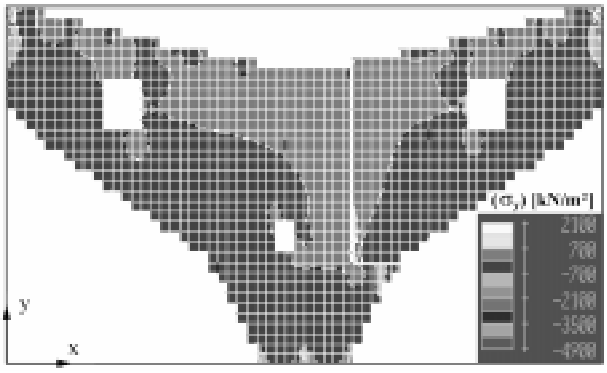

Fig. 13 σ_y normal stress diagram

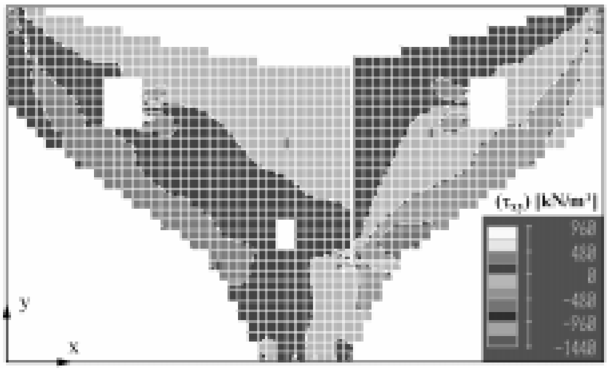

Fig. 14 τ_{xy} shear stress diagram

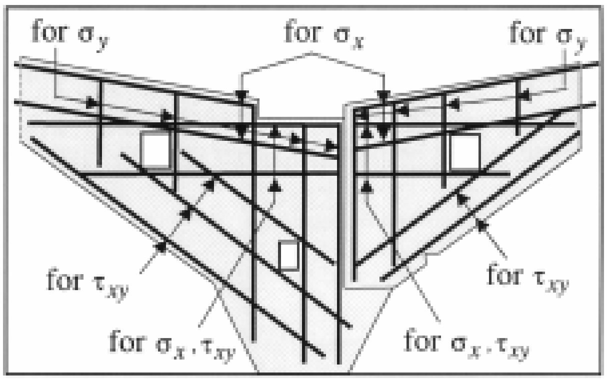

Fig. 15 Proposed reinforcement scheme

on the system are increasing. However, because of linear-elastic behaviour, the distribution of stresses doesn't change. σ_x and σ_y normal stress diagrams and τ_{xy} shear stress diagram in the connection zone are shown in Figs. 12, 13, 14 respectively. A reinforcement scheme is proposed for the connection zone on the basis of these stress diagrams (Fig. 15). It is suggested that the required reinforcement in the connection zone be placed with spreading among symbolic reinforcement (in the direction of reinforcement) shown in Fig. 15 for σ_x, σ_y and τ_{xy}.

5. Experimental study

Prefabricated test elements and mechanism of the experiment realized in the Structure Laboratory of the Istanbul Technical University are shown in Figs. 16 and 17, respectively (Uzgider 1995).

Experimental study was made on a single sample. Material properties of the test elements (precast elements, bolts, elastomer support) are the same as those of the numerical example. First, loading was increased up to service load in the experiment. After waiting 18 hours under service loads, unloading was performed. The load increment was made on this sample up to collapse load.

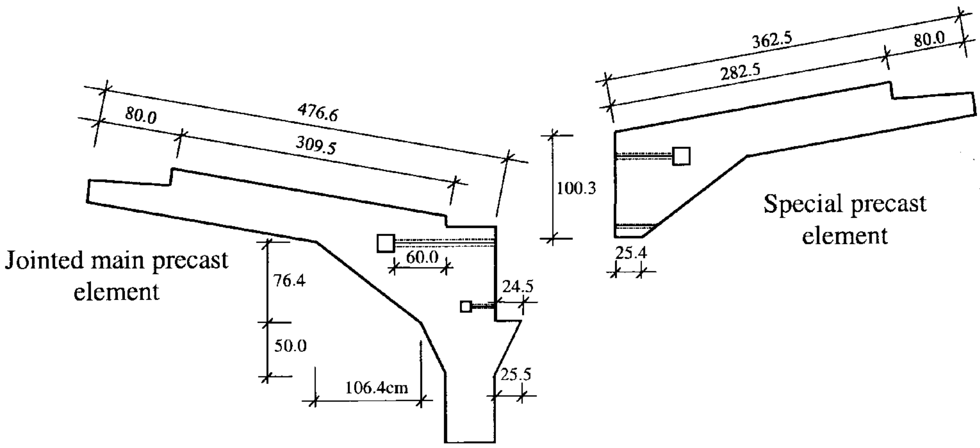

Fig. 16 Prefabricated test elements

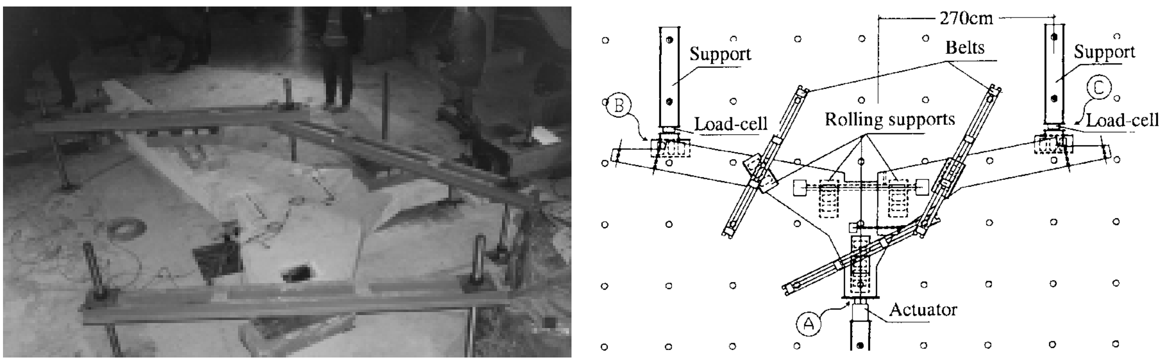

Fig. 17 Mechanism of the experiment

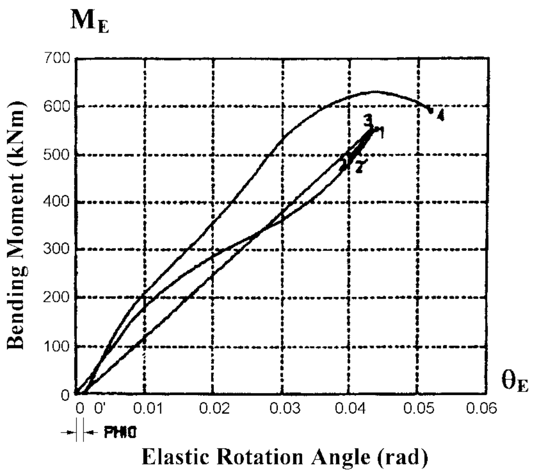

Fig. 18 M_E-θ_E Graphic (according to the results of the experiment)

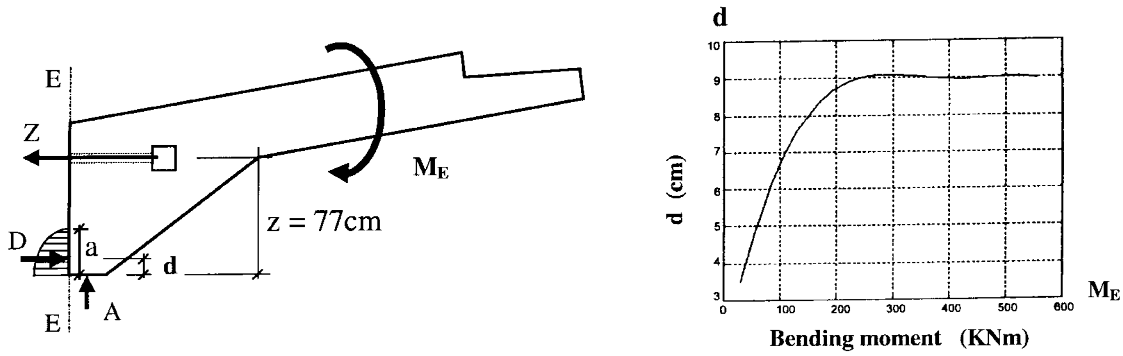

Fig. 19 Compression zone in the connection section and ***d*-*M*$_E$** graphic

Stresses and displacements of the system were recorded on a computer during the experiment. M_E-θ_E graphic drawn by obtained values is shown in Fig. 18. Curves of loading and unloading are shown in this graphic. After first loading-unloading, because of support settlings, an oddment rotation (PHIO) took place in the connection section. M_E-θ_E curve in the second loading is obtained more rigid than that of the first loading-unloading due to the fact that there are no more gaps in the system (Fig. 18). In order to determine length of the compression zone in the connection section, ***d*-*M*$_E$** curve was drawn by experimental data (where, ***d*** is distance from bottom edge of the vertical connection section to resultant point of the compression zone. Fig. 19).

6. Comparison of experimental results with numerical results

The length of the compression zone in the connection section (a) was found to be 5-10 cm from the numerical solution (Fig. 8). It was found nearly 9 cm from the experimental study (Fig. 19). It is noted that the value obtained from the experimental study is between two values obtained from the numerical solution. The elastic connection angle θ_E found in the experimental study was found to be 3.2 times greater than that of numerical results (Fig. 10 and second loading curve at Fig. 18). It is thought that this difference comes from some experimental errors and principal tensile cracks in the compression zone of the connection. For this reason, a new numerical study related to the determination of the connection's behaviour at the ultimate limit state is in progress. In this new study, the crackings at the prefabricated elements have also been taken into consideration. In addition, experimental studies are also continued to obtain more accurate experimental results.

7. Conclusions

Semi-rigid bolted beam connection applied in prefabricated reinforced concrete structures has been investigated. Moment-rotation relationship of the connection has been determined and an elastic rotation stiffness of the connection has been calculated. R_θ has been found 64655 (kNm/rad) The connection section of the frame has been assumed to have elastic, hinged, or rigid connections and a static solution under service loads has been performed for each case. Accordingly, it is concluded that if the connection section is assumed to be rigid or hinged instead of elastic, the solution will not be economic in some sections whereas not reliable in other sections. Therefore, R_θ values of connections in the precast structures are to be determined and this value is to be taken into the consideration in the structural analysis. Diagrams of stress distribution in the connection zone have been obtained for a more suitable reinforcement replacement. A reinforcement scheme has been proposed using these stress diagrams (Fig. 15).

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