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Review Article

Study of the Behavior of Joints with Full Continuity in Ground- Level Warehouses – A State of the Art Review

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Abstract

The demand for larger spans and heights for ground-level warehouses are constantly increasing the complexity of building requirements. This highlights the need for a concerted effort to gain a better understanding of construction methods and to have a deeper knowledge of the dimensioning of prefabricated structures. Even though the advantages of structural elements made in factory are obvious, there is a continuous decline of available specialists in this domain. Also, structural engineers, because of lack of experience and training, are often reluctant in redesigning prefabricated reinforced concrete structures. The design codes require the fulfillment of strict safety conditions, especially in the case of high stresses or in the case of seismic action, conditions that concern the limitation of rotations, displacements and the ductile failure mechanism [1].

Keywords: Ground-level Warehouses; Continuous joints; Full continuity joints; Behavoiur of joints

Introduction

Since the terms "joint" and "node" are sometimes used without clear distinction, the Romanian National Annex SR-EN 1993-1-8 [2] defines them as follows: a joint is represented by the physical components that connect the beam and the column and is concentrated at the location where the actual connection is made, while a node is represented by the joint to which the corresponding interaction zone between the joined elements is added. The main characteristics that a node must satisfy are: stiffness (Sj,ini), resistance to bending moments (Mj,Rd), and ductility (ϕu) (Figure 1). Based on the characteristics listed above and the M-ϕ response, nodes are classified into two: rigid nodes, hinged nodes, and semi-rigid nodes (Figure 2).

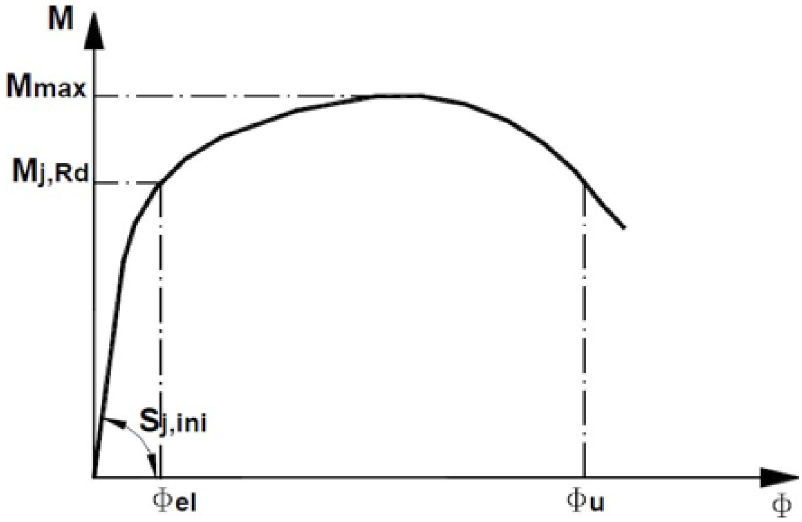

Figure 1: The characteristic response curve of a node resistant to moment [1].

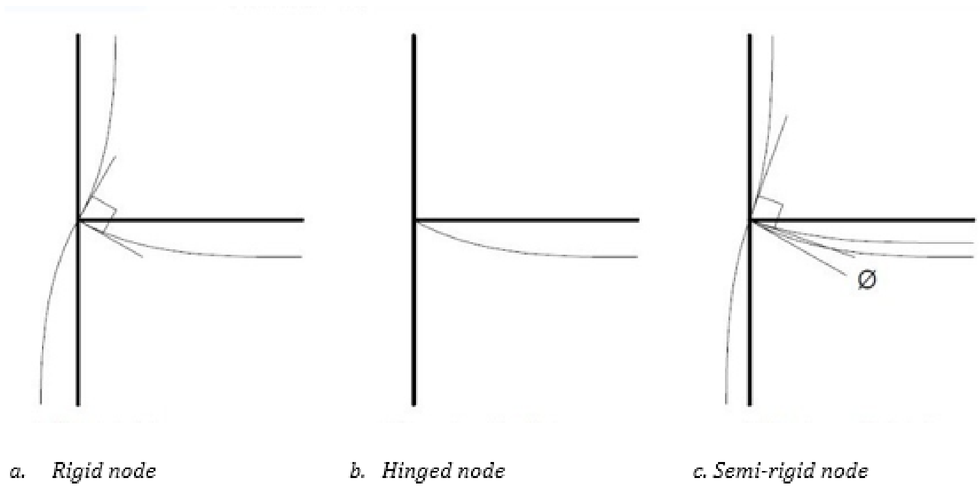

Figure 2: Types of nodes based on their rigidity [1].

Experimental and Numerical Studies

In order to achieve a framework with increased stiffness and redundancy, Bruno Dal Lago et al. [3] attempted to adapt the beam-column hinged node to a rigid node by activating a special mechanism after the floor installation, aiming to optimize structures with precast concrete elements in frames. The study was conducted on a commercial building with a height regime of G+2F. For seismic design, the modal analysis method with response spectra was employed. The building used for the numerical example has the following geometry: 4 spans of 12 m, 5 bays of 10 m, and a floor height of 5 m. For the experimental study, a frame made of prefabricated elements with 3 levels at a 1:1 scale was constructed, with floor heights of 3.4 m and 3.2 m. Three node configurations were analyzed:

a. Frame with hinged beam-column nodes,

b. Frame with rigid beam-column nodes at the roof and articulated nodes elsewhere,

c. Frame with rigid beam-column nodes throughout the structure.

Weaknesses in the study [3] indicate that the numerical models overestimated the vibration amplitude of structures with hinged nodes, likely due to the nonlinear behavior of hinged beam-column nodes with large rotations. Both numerical models underestimated the vibration amplitude of structures with rigid nodes, attributed to partial grout filling of some nodes in the experimental model.

From the numerical and experimental study conducted by Bruno Dal Lago et al. [3], the following aspects were observed:

a) The activation of mechanical connections to adapt hinged beam-column nodes to rigid nodes occurs after the application of self-weight loads, ensuring that end nodes are not subjected to bending from permanent loads.

b) The moment-curvature envelop of horizontal elements allows for a remarkable reduction in maximum values and optimal utilization of pre-stressed reinforcement.

c) Structures with prefabricated elements assembled “dry” (without injected mortar) with adaptable nodes exhibit reduced lateral displacements during seismic events compared to traditional prefabricated structures.

These aspects enable rational sizing of prefabricated elements while increasing the overall redundancy of the structure. JD Nzabonimpa et al. [4] conducted a nonlinear finite element analysis to reproduce the mechanical response of an experimental beam-column joint in prefabricated structures. The nonlinear finite element analysis is based on a cracked concrete model and performed in the plastic domain. The beam-column joint in prefabricated elements, realized through mechanical metal plates, was analyzed. The modeling considered the contact between surfaces defined by the metal plates in contact with concrete and the reinforcement to which they are fastened with nuts. The failure modes of the joint were studied, with the node being subjected to static loads.

It was observed that the beam-column joint models using mechanical metal plates employed in Finite Element Analysis represent much more attractive alternatives compared to highly expensive experimental models. The results obtained through analytical methods were similar to those obtained through experimental methods, indicating that the numerical model of the proposed joint can accurately predict its mechanical behavior. In the doctoral thesis of Halil Görgün [5], experimental trials were conducted to determine the M- ϕ curve for semi-rigid joints in prefabricated structures. Additionally, analytical studies were conducted to determine empirical formulas for calculating the effective length factor β for unbraced and partially braced frame columns. The experimental trials were performed on semi-rigid joints of a full-scale structure and isolated joints at a smaller scale. For the isolated joints, the component method was applied, summing up the deformations of joint elements and comparing them with the results obtained from experimental trials of joints in full-scale subassemblies. The mechanical behavior of joints subjected to experimental trials at full scale was analyzed through linear transformations resulting in empirically formulated parametric equations describing semi-rigid joints. For the analytical study of prefabricated frame structures, the following variables were considered: relative bending stiffness α of frame elements and relative linear stiffness Ks of joints.

Weaknesses in the study [5] were found in the suitability of each type of beam-column joint to be sized as a semi-rigid joint, which must take into account the load-bearing capacity and stiffness of the frame to which they belong. Halil Görgün proposed a joint sizing method for prefabricated structures that extends the calculation method used in BS 8110 and EC 2 standards. In the proposed sizing method, the load- bearing capacity and stiffness of the semi-rigid joint allow for the distribution of bending moments from the column to the beams to which they are connected.

With very promising results, Saeed Bahrami et al. [6] developed a joint capable of bearing bending moments and conducted nonlinear finite element analysis for the beam-column joint in prefabricated concrete subjected to lateral loads. In the same study, the following configurations were analyzed: beam- column joints in prefabricated concrete structures with continuous columns, beam-column joints with prefabricated columns equipped with a bracket connection using bolts (inverted “E” connection), and beam-column joints with prefabricated columns equipped with a bracket connection using welding.

Following the numerical analyses, it was found that the prefabricated beam-column joints proposed by Saeed Bahrami et al. [6] are approximately 98% similar to monolithic reinforced concrete nodes in terms of load-bearing capacity. The studied prefabricated beam-column joints are about 80% similar to monolithic nodes regarding stiffness under lateral displacements and approximately 80% similar in terms of ductility. A Finite Element Analysis was conducted using the LS-DYNA software by Hussein M. Elsanadedy et al. [7]. In their work [7], a numerical analysis using the Finite Element Method (FEM) was performed to assess the risk of progressive collapse at rigidified prefabricated concrete beam-column joints. Solutions for stiffening prefabricated concrete structure joints were attempted to prevent their progressive collapse. The risk analysis for progressive collapse was carried out in the scenario of removing a central column.

The risk of progressive collapse was analyzed on a single-story frame with two bays, considering the hypothesis of failure of the central column. Two scenarios were analyzed: when the joints between prefabricated elements are unrigidified with plates and when they are rigidified with plates. The modeling of the two structures considered the following: material nonlinearity (including strain rate) for concrete, steel reinforcement, neoprene plates, steel stiffening plates, and contact between joint elements. The numerical models were compared with the results of experimental tests conducted on three structures at a 1:2 scale. The three structures used in the experimental tests were: a prefabricated control structure with unrigidified joints, a monolithic reinforced concrete structure with continuous beams, and the prefabricated structure with rigidified joints [7].

The results of the experimental tests revealed that compressive arching and the catenary effect manifested in beams through the yielding of longitudinal reinforcement by pull-out. The increase in compressive arching and the catenary effect depends on the configuration of the node and the percentage of longitudinal reinforcement in the beam. An extremely important aspect affecting the quality of structural elements is corrosion. The effect of corrosion on joints between prefabricated concrete elements was analyzed by Jun Yang, Tong Guo, and Shun Chai [8] using a frame structure with prestressed reinforced concrete elements. Experimental tests were conducted on 5 structures with varying degrees of corrosion, subjecting them to cyclic loading. The following parameters were studied and compared: crack propagation, shape of hysteresis loops, shape of enveloping curves, load-bearing capacity of joints, ductility, and energy dissipation capacity.

Following the experimental trials, it was observed that concrete cracking and reduction in the steel reinforcement section due to corrosion significantly impacted the yield strength of the steel, but had a relatively small influence on the ultimate strength. Due to the asymmetry of the beam-column joint, the distribution of corrosion was uneven in both the upper and lower reinforcements of the beam. To conduct fatigue analysis after a low number of loading-unloading cycles, Bin Du et al. [9] developed a model of prefabricated elements with semi-rigid joints. The study was carried out through experimental trials where the models were subjected to cyclic loading, with joints welded. The experimental analysis considered both external actions and internal parameters of the joint. To better capture the fatigue behavior of nodes in prefabricated structures, the numerical model was adjusted to match the experimental results, increasing the influence of maximum deformation on node deterioration.

After the modifications, the accuracy of the numerical model used in fatigue analysis significantly improved compared to the experimentally obtained results. The proposed numerical model provides a reliable method for analyzing potential deteriorations and failure modes that may occur at joints in prefabricated structures and can contribute to seismic analysis and sizing of these types of structures. Marcela Novischi Kataoka et al. [10] described the nonlinear finite element analysis of a joint consisting of a column, beam, and prefabricated concrete slab. Although the joint underwent experimental testing, due to the complexity of the beam-slab-column joint, numerical analysis was conducted to better understand the mechanical behavior. The internal connection comprises column corbels, dowels, and continuity bars passing through the column.

The numerical model analyzed through FEM was validated by comparing the results with those from experimental analysis, with the numerical analysis results demonstrating a good ability to represent the mechanical behavior observed in experimental trials. The joint underwent a parametric study in which the diameter of the continuity bars and the properties of the monolithic concrete varied. The numerical analysis of the joint yielded values of stresses, deformations, and displacements that were not obtained from experimental trials. The parametric study revealed that the diameter of the continuity bars has a greater influence on the behavior of the prefabricated element joint than the compressive strength of the concrete. A new type of prefabricated beam-column joint was proposed by H.-K. Choi, Y.-C. Choi, and C.-S. Choi [11]. The joint configuration was designed to ensure structural continuity of the reinforcement in the beam. The joint was designed based on the concept of a rigid column - flexible beam model. For the experimental study, five interior beam-column joints were analyzed at a scale of 1:2. Four of them were prefabricated elements, and one was monolithic reinforced concrete. The joints were subjected to loading simulating seismic action.

The beam reinforcement was designed to develop plastic hinges in the beam and to impose large inelastic shear forces at the joint. From the experimental results, it was observed that the plastic hinges developed in the beam controlled the failure mechanism of the joint, and the strength of the joint with the proposed configuration was 1.5 times higher than that of the monolithic reinforced concrete joint. The objective of the study conducted by Ulla Kytölä, Olli Asp, and Anssi Laaksonen [12] was to investigate and evaluate the bending behavior of the continuity joint between precast concrete beams with prestressed reinforcement. The behavior of the continuity joint was evaluated under negative bending moment. In the experimental program, four "T" cross-section corbels were analyzed and loaded until failure. The main parameter in the experimental tests was the intensity of the prestressing force applied to the two connected beams. The reinforcement percentage of the continuity joint was high. The bending capacities and moment-rotation curves were calculated through numerical methods.

Following the experimental trials presented by Ulla Kytölä et al [12], the following observations were made:

a. The magnitude of the prestressing force in the joint between beams did not have a significant effect on the ultimate load-carrying capacity of the continuity joints.

b. The magnitude of the prestressing force between beams influenced the overall structural behavior under large loads. The concrete cover layer at the beam's soffit began to crack at considerably smaller loads compared to the ultimate load-carrying capacity. A higher percentage of reinforcement in the joint between beams resulted in lower loads causing visible cracks in the lower part of the critical sections. The bending moment at the time when visible cracks appeared in the compressed zone of the beam (at the soffit) had values similar to those of plain concrete.

c. The top reinforcement in the support zone yielded in general for all tested beams long before reaching the ultimate load-carrying capacity, regardless of the prestressing effects and the fact that the joint zone was over-reinforced. The interaction curves of moment-rotation resulting from the experimental trials indicated ductile failure of the joint. This mode of moment redistribution would occur in the case of an indeterminate statically beam with a similar joint.

d. The critical section where the ultimate load-carrying capacity was first reached had approximately the same position where the prestressing force reached its transfer length and became fully effective. Failure always occurred outside the diaphragm.

The results of the study [12] showed that in the design of a continuity joint, the uncracked concrete model should be considered, and the effect of prestressing force cannot be neglected in calculating the ultimate bending moment. According to these hypotheses, after reaching the ultimate load, the structure still maintains much of its stiffness.

An experimental investigation of the continuity of precast prestressed concrete double “T” floor slabs was conducted by Ferdinand S. Rostasy [13], aiming to investigate the stiffness and solidarity of the continuity joint. The continuity joint was created by placing bent bars with medium strength along the supports over which concrete was poured. The space between adjacent double “T” slabs was filled with concrete to form transverse diaphragms. For the experimental trials, 8 symmetrical double “T” slabs with a length of 5.80 m were used, subjected to negative bending moments. The main parameters studied were the prestressing force and the amount of continuity reinforcement. Additionally, four continuous beams with 2 spans, totaling 19.50 m in length, were subjected to similar experimental trials. The main parameters studied for continuous beams were the quantity of redistributed design bending moments and the prestressing force.

In this experimental study, the effects of slow flow and shrinkage of concrete were not taken into account. The yield strength of the continuity reinforcement should be higher than the tensile strength at which the concrete in the floor slab and in the cover layer of the double “T” section cracks. This aspect would prevent the continuity reinforcement from yielding immediately after concrete cracking and, consequently, would limit the opening of cracks. The results of the experimental trials conducted on the double “T” slabs showed that within a certain practical range of reinforcement percentage for the continuity bars, the precompression force does not influence the ultimate bending moment capacity of the continuity joint. The behavior of continuous beams designed using arbitrary modifications of the calculated bending moment in the support sections indicates that structures of this type, for which this design approach is applied at the limit state, should behave satisfactorily under service loads. The experimental trials presented in [13] showed that if the reinforcement index of the support sections is less than half of the balanced reinforcement index, then the overall load factor of the structure should be greater than or equal to the load factor used for the design of individual sections. Additionally, a reasonable estimate of the ultimate load-carrying capacity of the structure can be made based on the limit state analysis assuming that the bending moments are completely redistributed when it reaches the brink of collapse. The experimental trials also showed that if this type of continuity joint is applied to prefabricated element structures, then the behavior under external loads should be satisfactory and should have an adequate safety factor.

Between 1964-1965, Ned H Burns [14] conducted various experimental trials on beams with continuity joints to study their mechanical behavior. The first series of experimental trials focused on beams made of precast prestressed concrete. The second series of experimental trials focused on beams made of precast concrete with post-tensioned reinforcement. The study aimed to establish continuity between precast concrete beams with prestressed reinforcement to achieve an economically optimal structure. According to the study [14], continuity between precast concrete beams with pretensioned reinforcement can be achieved in different ways to produce structurally efficient elements, and the use of pretensioned bars in the joint seems to have advantages in terms of crack control. Therefore, post-tensioning is not necessary when using these bars in continuity joints. Beams in which the continuity joints include a combination of post-tensioned, pretensioned, and conventional reinforcement exhibited satisfactory mechanical behavior.

Conclusions

From the numerical examples regarding prefabricated structures, it can be observed that higher values of stiffness coefficients reduce the lateral displacements of prefabricated structures. However, special attention must be paid to beam-column joints during the design phase, as poorly configured connections between beams and columns can lead to large lateral displacements under horizontal loads. Continuity between precast concrete beams with pretensioned reinforcement can be achieved in different ways to produce structurally efficient elements. The use of pretensioned bars in joints seems to have advantages in terms of crack control. Thus, post-tensioning is not necessary when using these bars in continuity joints. Beams in which continuity joints include a combination of post-tensioned, pretensioned, and conventional reinforcement exhibited satisfactory mechanical behavior. The reserve strength ratio incorporates the concepts of energy balance and an inelastic displacement spectrum and can be used to avoid premature yielding, large displacements, and unfavorable modes of failure.

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