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NUMERICAL INVESTIGATION OF A MULTI-LINEAR MODEL FOR PRECAST HYBRID BEAM-COLUMN CONNECTIONS

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ABSTRACT: Moment-resisting hybrid ("emulated-welded") connections consisting of welded beam-corbel plates at the bottom and in situ concrete at the top of the beam are widely used in the precast industry in Türkiye. Experimental studies on precast hybrid connections have shown that changes in the mechanical properties of reinforcing bars may occur due to welding. In this study, the experimental and numerical cyclic behavior of the interior and exterior connections of hybrid beams and columns is presented. A lumped plasticity approach and simulation tools in the SeismoStruct computer program were used to perform numerical simulations of the connections. A multi-linear cyclic model was assigned to the rotational spring parameters at the beam ends for the lumped plasticity modeling approach. Comparison of numerical and experimental results in terms of strength, and the models satisfactorily computed the cyclic force– deformation response.

Keywords: Precast, hybrid connections, lumped plasticity model, cyclic behavior

1. INTRODUCTION

Precast structures are rapidly increasing because of their advantages over conventional structures. The design and application of precast structures becomes more effective as they are built off-site, and the homogeneity of all factors makes them a better option. Other major advantages include time saving and cost effectiveness. Single-story precast structures are common in areas with active seismicity. A critical concern is the response of beam-column connections during an earthquake. Observational studies of past earthquakes indicate that the strength and stiffness of beam column connections are not adequate to counter seismic activity. (Senel and Palanci, 2013; Ozden and Meydanli, 2003; Saatcioglu et al., 2001). Beam–column connections play an important role in the overall integrity of structures, and their response during earthquakes can determine the safety or failure of structures. There are two general classifications of connections in precast concrete, namely emulative (wet) and dry connections and a hybrid type of connection with emulative and mechanical parts as well, which combines both. (Negro and Toniolo, 2012). Hybrid connections with emulative-welded parts are the most common in practice, especially in areas where seismic-resistant design is required, such as Türkiye. Emulative-welded hybrid connections (MAB 3) are produced by welding longitudinal rebar to the corbel plates, followed by casting concrete in the upper region of the beam and column elements. Extensive experimental and numerical studies have been conducted on the seismic behavior of precast connections. However, there is currently limited research on how hybrid (emulative welded) connections behave. Ertas et al. (2006) studied various types of precast moment-resisting beam-column connections under cyclic loading. They analyzed energy dissipation, stiffness degradation, and hysteretic behavior. Similarly, Yuksel et al. (2015) examined two variations of exterior beam-column connections to investigate seismic behavior

under different loading conditions, focusing on energy dissipation, ductility, and strength. Furthermore, the examined test specimens were simulated on precast connections using OpenSees (2000). A satisfactory approximation was obtained by comparing the numerical results with the experimental test outcomes. Feng et al. (2018) focused on the seismic efficiency of diverse precast concrete connections between columns and beams and finite element modeling of precast joints. Nonlinear finite element (FE) analysis was performed using ABAQUS software. According to their findings, the numerical model could capture the seismic performance of the precast connections. Aninthaneni et al. (2018) analyzed the seismic behavior of dry beam-column connections and a wet jointed concrete frame system. A comparison of these two types of connections was conducted on the basis of the experimental and analytical results. To simulate the tested frame systems, the researchers used analytical models. This study investigated the principles of pivot and IMK peak-oriented hysteresis curves and concluded that established models effectively simulate hysteresis behavior in precast concrete frame systems. Moreover, they compared the energy dissipation features and stiffness degradation of each numerical and tested system. Tarabia et al. (2021) studied monolithic and bolted precast beam-column joints. The Seismostruct program's non-linear link elements helped predict the cyclic behavior of the tested connections. The numerical model definition utilized the modified IMK pinched curve and the bilinear-modified Takeda. On the basis of the results and comparisons, nonlinear finite element models could be implemented effectively. the tested specimens were based on empirical observations and comparisons. In the paper by Zhang et al. (2023), a comprehensive modeling strategy for wet-type precast concrete beam-column connections was established using OpenSees. They constructed two numerical models featuring both two- and three-dimensional fiber components. Subsequently, they assessed both models using experimental data. The results demonstrate that the 3D-based model, which considered more parameters, provided better prediction accuracy in the simulation of wet-type precast connections.

In seismic codes (e.g. ACI 318.05 2005a; Turkish Building Earthquake Code (TBEC) 2018), it is necessary to perform analytical modeling or experimental studies to determine the seismic behavior equivalence between newly proposed precast moment resisting connections and monolithic connections. This study seeks to understand the nonlinear modeling parameters of precast concrete moment-resisting emulative welded (MAB 3) connections through numerical investigation. This study provides an understanding of the seismic performance of these connections, imparting valuable implications for design considerations in regions prone to seismic activity.

2. NUMERICAL SIMULATION MODELS

This study examines the response of hybrid beam-column connections under cyclic loading conditions using an interior test specimen (SP3) as outlined by Girgin et al. (2017) and an exterior test specimen (GOK-W) as studied by Ertas et al. (2006). Analytical modeling approaches can be used to simulate the nonlinear behavior of the reinforced concrete elements. These approaches fall into two categories: (i) lumped plasticity models and (ii) distributed plasticity models. For this study, a lumped plasticity approach was adopted as opposed to using distributed plasticity models or connections. For beam and corbel sections, linear frame elements were used, and for columns, an inelastic force-based frame element was used with 200 individual fibers and 10 integration points. The geometric properties and numerical models adopted for the specimens, which were employed according to the lumped plasticity approach, are shown in Figures 1 and 2. The precast hybrid interior connection specimen (SP3) was tested in an experimental research program performed by Girgin et al. (2017) and was considered in this study. Longitudinal bars at the bottom of the beam were welded to the endplate of the beam. The column was axially loaded at approximately 8% of its axial capacity during cyclic reversals. Details about the beam and column sections, including the reinforcing properties and geometry, are shown in Figure 1. The beam was 300 mm wide and 450 mm height, consisting of 300 mm of cast-in-place (CIP) concrete and 150 mm of topping concrete. The cross-section of the column was 400 mm 400 mm with a 300 mm corbel length and a 150 mm gap along the precast concrete beam. The shear span to beam depth ratio (a/d) for the specimens was 3.15. On the day of testing, the average compressive strength of the concrete was 42 MPa for the beam and column elements and 35 MPa for the cover concrete. The beam bottom longitudinal reinforcing bars were welded to an 18-mm diameter steel plate had a yield strength of 487 MPa and ultimate strength of 589 MPa. During the test for SP3, the beam bottom

longitudinal rebars buckled at a drift ratio of 2.75% and cracked near the beginning of the weld areas at the second cycle of 3.5% drift ratio.

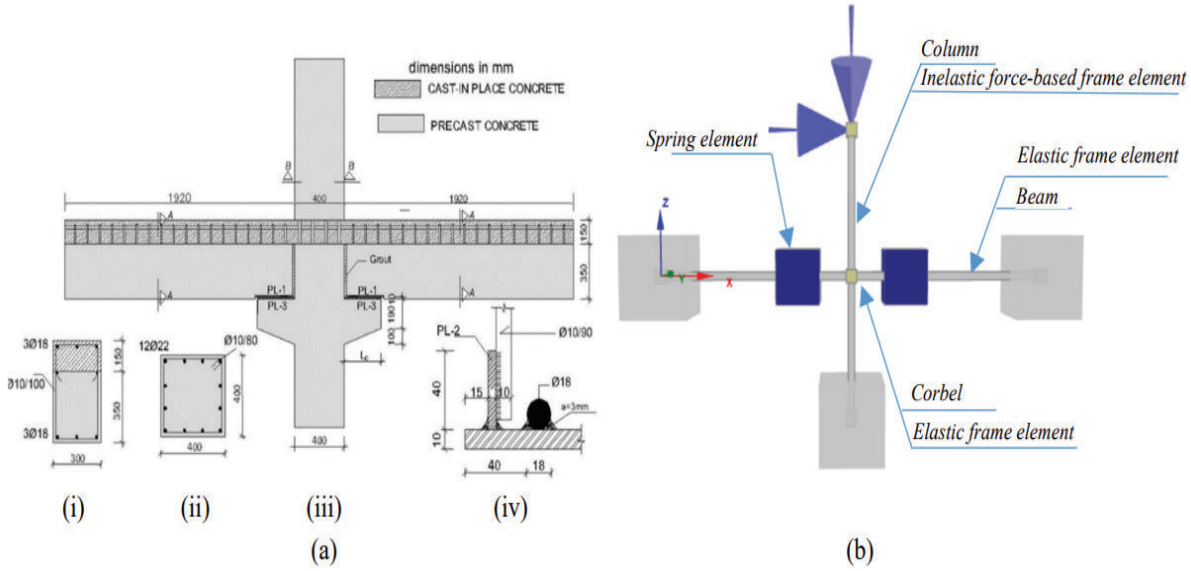


Figure 1. SP3 (a) (i)Beam section, (ii) column section (Girgin et al., 2017), (iii) details and dimensions of the hybrid beam– column connection, (iv) welding detail of the beam, and (b) numerical model in Seismostruct (Dinçer et al., 2023).

The GOK-W precast exterior connection specimen was tested in the experimental research program conducted by Ertas et al. (2006) and is considered in this study. The precast beam was 300 mm wide and consisted of 300 mm cast-in-place (CIP) and 200 mm topping concrete sections. The column had a cross-section of 400 mm 400 mm with a corbel length of 350 mm and a gap of 200 mm along the precast concrete beam. On the day of the test, the average concrete strength was reported to be 57 MPa for the beam and column elements and 55 MPa for the topping concrete. The beam bottom longitudinal rears were welded to a steel plate with a diameter of 20 mm, yielding 503 MPa and an strength of 662 MPa. During the GOK-W specimen test, the first diagonal crack was reported at a 2.2% drift ratio, and the beam bottom rebar ruptured during the first cycle at a 3.5% drift ratio.

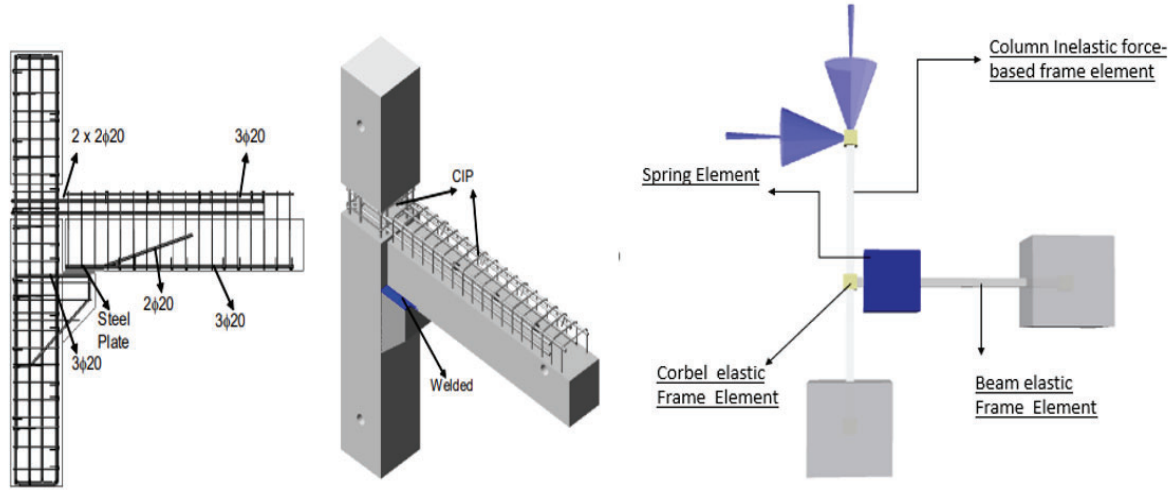
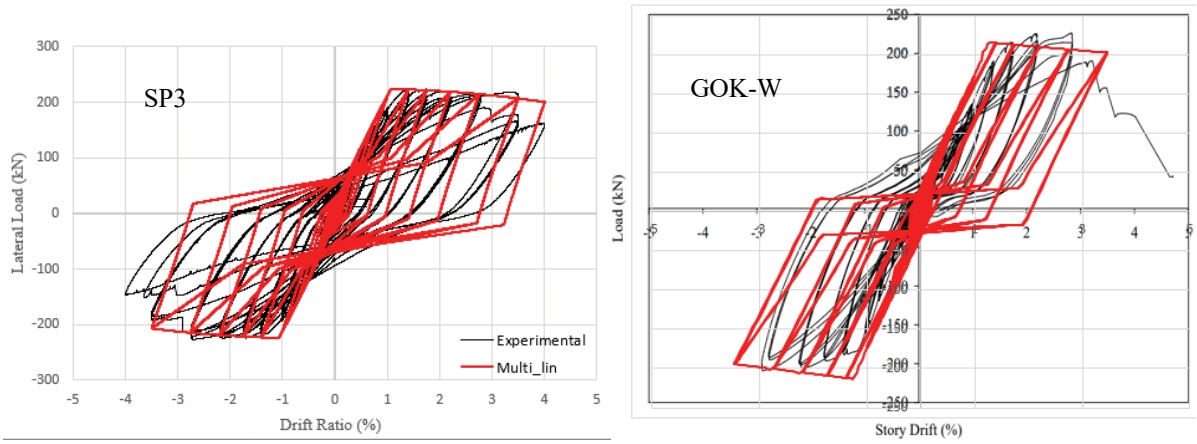


Figure 2. (a) GOK-W specimen details and (b) numerical model of the specimen

Table 1 lists the different parameters used in SeismoStruct for both SP3 and GOK-W specimens. After modeling these specimens using the above parameters, the numerical results showed good agreement between the experimental tests in terms of strength and stiffness, as shown in Figure 3.

Table 1 : Parameters used in the *S*eismostruct for modeling non-linear connections.

Parameter	**SP3**	**GOK-W**
Initial Flexure Rigidity (EI)	23200 kNm	23200 kNm
Cracking Moment (M_{cr})	32 kNm	32 kNm
Yield Moment (M_y)	181 kNm	350 kNm
Yield Curvature ($Ø_y$)	0.012	0.012
Yield Curvature ($Ø_u$)	0.17	0.17
Stiffness-degrading parameter (HC)	200	200
Ductility-based strength decay parameter (HBD)	0.001	0.01
Energy-based strength decay parameter (HBE)	0.5	0.01
Slip Parameter (HS)	0.5	0.2

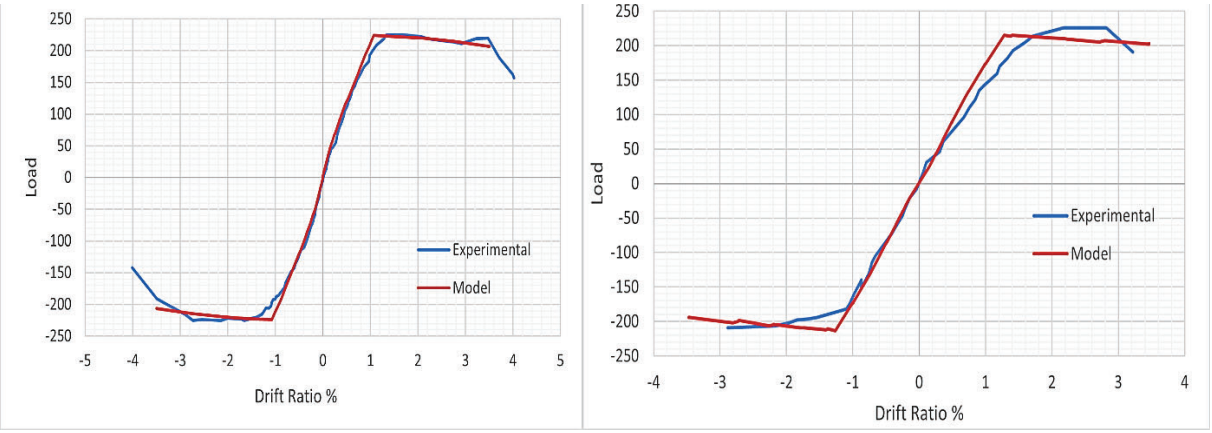


(a) (b)

Figure 3. Comparison of experimental and analytical responses for the (a) SP3 and (b) GOK-W specimens

3. ANALYSIS RESULTS

After modeling the specimens and comparing their responses with the experimental data, the next step is to use the output data for different analyses. The analysis considered in this study is backbone curve analysis. The backbone curve in structural analysis is a graphical representation of the relationship between the applied load and the resulting deformation in a structure. It shows the response of the structure/member under increasing load. Typically, the backbone curve has a linear response in the elastic range, but the curve transitions into a non-linear behavior when loading continues to increase. This provides insight into the yielding and plastic behavior of the structure. The backbone curve is a fundamental tool for understanding the overall performance of structures, especially in seismic and non-linear analyses. It aids in identifying critical points such as yield and ultimate capacities. Backbone curves for SP3 and GOK-W specimens were drawn using the output data of the model and plotted alongside the experimental data. Figure 4 attached below shows the graphical representation.



(a) (b)

Figure 4. Backbone curves of the (a) SP3 and (b) GOK-W specimens

The next step in the analysis is to determine the effective ductility capacity, $\mu_{eff.}$ Ductility is the ability of a structure or material to undergo significant deformation without losing its load-carrying capacity. The effective ductility capacity was calculated in accordance with the FEMA P-795 guidelines (2011), which provide guidelines for measuring the ductility value for such cases. According to FEMA P-795, ductility measurement includes the following parameters: Ultimate load(Q_M), Ultimate deformation(Δ_U) defined as deformation at 0.8 Q_M, Initial stiffness (K_I) (based on force and deformation at 0.4Q_M), Effective yield deformation, $\Delta Y_{,eff}$ ($\Delta_{Y,}$ $eff = Q_M/K_I$), and Effective ductility capacity(μ_{eff}) can be calculated as ($\mu eff = \Delta_U / \Delta Y_{,eff}$). Table 2 shows the results after the calculation for both specimens.

Table 2 : Numerical analysis results in terms of ductility

Specimen	Loading Type	*QM*	0.8*QM*	0.4*QM*	Δ*Y,eff*	Δ*U*	jeff	Average jeff
SP3	Push	223.83	179.06	89.53	0.81	3.36	4.17	
	Pull	223.81	179.05	89.52	0.79	3.1	3.9	4.035
GOK-W	Push	213.83	171.06	85.53	0.725	3.25	4.48	
	Pull	215.43	172.34	86.172	0.8	3.31	4.13	4.31

4. CONCLUSIONS

Numerical simulation of SP3 and GOKW specimens was performed using SeismoStruct, and the results were validated by comparison with experimental data. The lumped plasticity model for connections and the fiber-based approach for columns give satisfactory responses under cyclic loading. The backbone curve provides insight into the key factors of structural performance, such as yield and ultimate points. Under the guidelines of FEMA P-795, the calculation of effective ductility under cyclic loading is a key parameter in seismic design. The outcomes contribute to the knowledge base for the design and assessment of similar structural connections in seismically active regions, thus improving the overall resilience and safety of precast construction systems.

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