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Performance of Precast Concrete Splice Sleeve connection under Seismic and Impact loads

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INTRODUCTION

ACI 349 does not endorse the use of precast concrete in safety-related applications due to concerns over its lateral load-resisting behavior. Despite this limitation, precast concrete has a well-established track record in large-scale infrastructure projects, including nuclear facilities in seismically active regions. Since there is potential for using precast components in reactor buildings specifically for shielding applications, this study aims to investigate the performance of the grouted splice sleeve connection under impact and seismic forces.

One of the key innovations facilitating the use of precast concrete is the use of emulative detailing. The splice sleeve connection is one of the most common systems used for emulative detailing. This method involves inserting reinforcing bars into specially designed sleeves filled with high-strength grout, creating a continuous load path across precast joints. A schematic for this type of connection is presented in Figure 1 and Figure 2. In most cases, splice sleeve connections are qualified as type 2 connections per ACI 349. Accordingly, the connection archives 150%F_y of the rebar capacity. Splice sleeves offer adequate performance under seismic and impact loads, ensuring structural continuity and reliability. These connections have become a potential candidate for developing emulative detailing for precast components. Emulative detailing is a type of detailing that ensures that a precast concrete connection will behave similarly to a monolithic cast-in-place concrete connection. ACI 550 provides a detailed procedure to qualify precast concrete connections as emulative connections. Recently, many researchers have utilized ACI 550 testing protocols to investigate the performance of these connections under seismic loads [1] [2] [3]. The results indicate that for seismic demands, the performance of these type of sleeve connections is equivalent to cast in place concrete. Yet there is scarcity in the work done to investigate the performance of these connection under impact loading.

This paper examines the performance of splice sleeve connections under extreme loading conditions. It employs high-fidelity finite element analysis to compare their behavior with traditional cast-in-place concrete connections under seismic and impact loading. The analysis is conducted using the LS-Dyna explicit analysis tool.

The author [4] performed prior validation of the modelling methodology against impact loading. In this study, the seismic behaviour of the constitutive models is verified using a cyclic test of a cast-in-place (CIP) beam-column moment frame [5]. Subsequently, the validated model is applied to analyze a precast moment frame connection with splice sleeve detailing, evaluating its ductility under the same cyclic loading. Finally, the model is extended to investigate the impact response of a shear wall, employing both

flexural and shear strike scenarios with a 4'x8' projectile at 328 ft/sec, replicating the loading conditions from a Sandia National Lab fuel dispersion study [6].

Figure 1. Splice sleeve connection

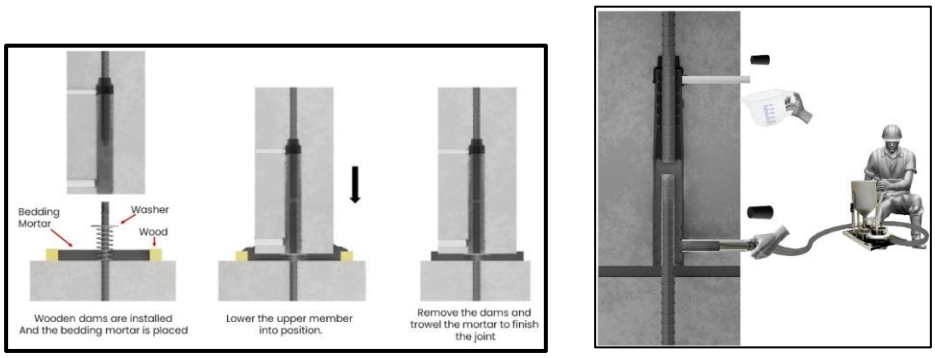


Figure 2. Assembly of the splice sleeve connection

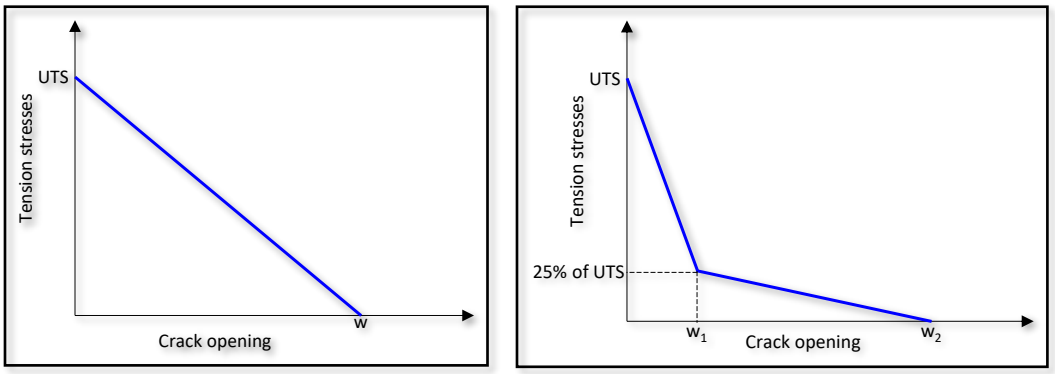
FINITE ELEMENT MODELLING APPROACH.

The analysis is developed using an LS-Dyna explicit finite element modeling tool. The concrete is modeled using a solid continuum, the rebars are modeled using discretized beam elements, and the connectivity between the rebars and the concrete is achieved using nodal-to-nodal connectivity.

The constitutive model used to simulate the concrete behavior under cyclic and impact loading is the Winfrith constitutive model. The material model is a linear material fitted to an Ottosen [7] failure surface. The material can depict three failure modes: compression, shear, and tension. The material flows plastically for compression and shear failure; for tension failure, the material fails by forming up to three orthogonal cracks. After crack initiation in tension, the crack normal stress decays in one of two forms: 1) as a linear function for MAT_084 which is a Winfrith material model with the strain rate effect turned off, and 2) bi-linearly for MAT_085 which is a Winfrith material model with the strain rate effect turned on as presented in Figure 3. For steel material, a piecewise linear plasticity model simulates the steel behaviour under impact and cyclic loading. The constitutive model defines an arbitrary stress as a function of the strain curve and an arbitrary strain rate dependency. The stress-strain relation used for the rebars is engineering stress-strain curves, since the beam elements do not capture the nicking behaviour. For impact cases, the material Dynamic Increase Factor (DIF) is identified following the values recommended by the Nuclear Energy Institute [8].

The model is discretized using brick elements for the concrete continuum and discrete beam elements for the rebars. The element formulation for the brick elements is Constant stress solid element (Element Formulation-1). For the beam elements, Hughes-Liu with three cross-section

integration points is used. The stiffness hourglass formulation is used to control the house glass energy of the single stress element.



(a) (b)

Figure 3. Strain softening curves (a) For MAT_084 (b) For MAT_085

VALIDATION AND VERIFICATION FOR SEISMIC BEHAVIOUR OF THE CONSTITUTIVE MODEL

A cast-in-place concrete moment frame is used as a benchmark for evaluating the constitutive model's performance under cyclic loads. The problem is presented in Figure 4 [5]. In this experiment, the displacement was applied to the top hinge (location of P in the figure). The beams are only restrained in the vertical direction at the two hinge locations shown in the figure. The bottom connection is also a hinged connection to allow the column to rotate and apply the cyclic moment to the beam column connection. The concrete compressive strength is 5.06 ksi. The properties for the rebars are presented in Table 1. The LS-Dyna model for this connection is presented in Figure 5(a). The applied displacement is presented in Figure 5(b). The load displacement of the specimen is compared to the load displacement values extracted from the finite element model as presented in Figure 6. As presented in the figure, the constitutive models depicted the ductility and the strength of the CIP connection with very good accuracy. The maximum strength for the connection is identified in the experiment at 2.5% drift ratio with Vu=798kN. The LS-Dyna model identified the strength for the connection at a 2.3% drift ratio with Vu=803kN. The cracking pattern from the FEM is compared to the one recorded in the experiment at 3% drift and is presented in Figure 7. The results indicate good matching between the FEM and the experimental data.

Table 1: Properties of the test specimen

Property	Callout in Figure 4	Bar No	f_y (ksi)	f_u (ksi)
Column vertical rebars	14D35	#11	71.5	87.7
Columns stirrups	D16	#5	63	84.8
Beam rebars top	4D32	#10	67.9	86.9
Beam rebars bottom	2-D25	#8	67.1	91.4
Beam rebars bottom	2-D29	#9	74.5	94.4
Beam stirrups	D13	#4	72.9	84.6

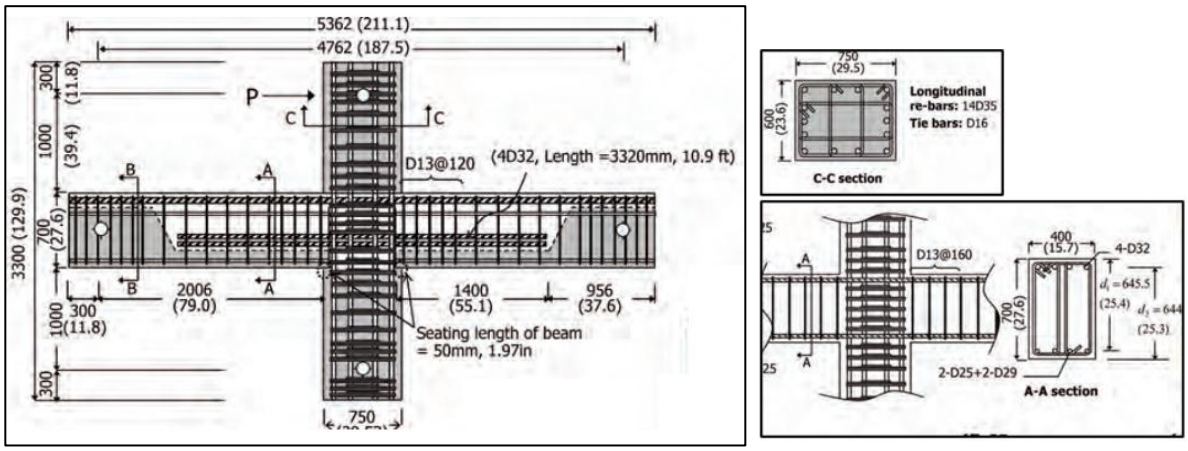
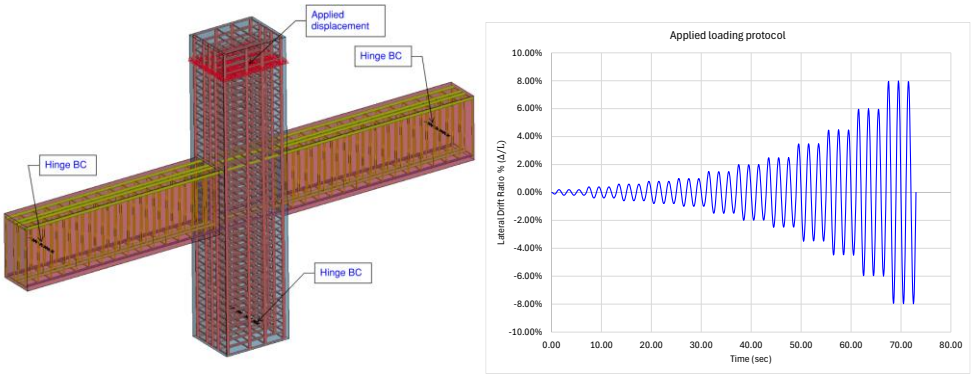


Figure 4. Tested concrete moment frame [5].



(a) (b)

Figure 5. FEM developed for validation. (a) 3D model configuration (b) applied displacement.

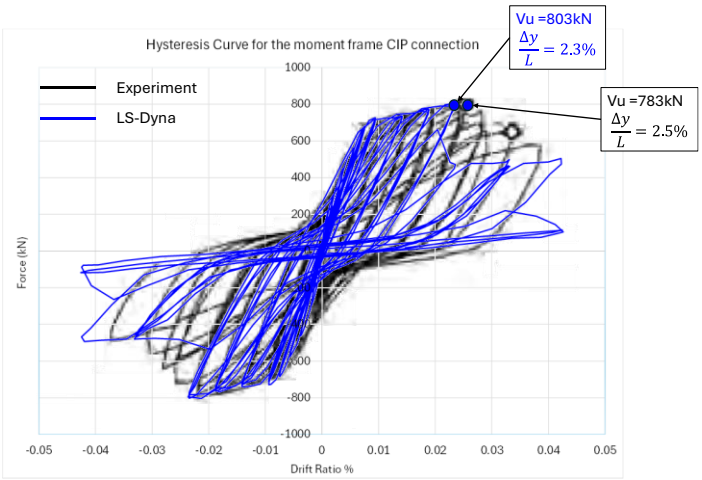


Figure 6. Force Displacement relation from the experiment and the LS-Dyna FEM

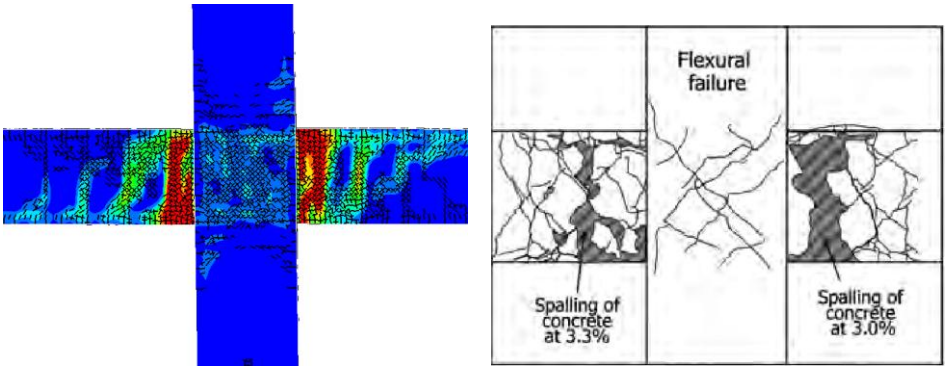


Figure 7. Comparing the FEM concrete cracking pattern to the experimental results.

INVESTIGATING THE PERFORMANCE OF SPLICE SLEEVE IN CYCLIC BEHAVIOUR.

To assess the splice sleeve's performance under cyclic loading, the same frame connection is used, except the connection between the beams and the columns is re-modelled to reflect the splice sleeve system. Building the splice sleeve and integrating it into the precast system is essential in reflecting the connection strength. Figure 8 presents a common method for connecting beams to columns on the site. In this approach, the beam end is left to be cast on-site, which can be identified as "Wet Joints". This procedure aligns with ACI 550 and ensures the developed detailing is an emulative detailing that mimics cast-in-place concrete behaviour. Existing research [5] [9] showed that using this approach, the connection behaves identically to cast-in-place concrete. The other standard installation method is known as "Dry Joints," where grout is only applied to the sleeve connection, as presented in Figure 9. Currently, there is no code or standard that describes how the injected grout in the sleeve, which will fill in the small gap between the two precast pieces, will behave under different loading conditions. This article modifies this interface layer using a contact algorithm with specific cohesion strength. The proposed value for the cohesion at this interface layer is 50 psi. This value is a conservative value selected by the authors based on similar research conducted to assess the cohesion strength between the concrete and the flat steel plates in the Steel Plate Campsite System (SC-walls). Sener et. al [10] recommend a cohesion value of 50 psi at this smooth interface layer. The author conducted a literature review to identify other sources for estimating the strength of this layer. Sarhan et. al [11] tested various smooth steel plate surfaces to estimate the bond strength at the interface layer. The experimental results indicated a minimum value of 319 psi for the cohesion at the interface layer between concrete and a smooth steel plate. Ertzibengoa et al. [12] conducted a more comprehensive study, investigating a wider range of materials (carbon steel and stainless steel) and steel configurations (deformed and undeformed rebar, rectangular plates). The minimum value recorded in his experiment was for a stainless steel plate with 217 psi cohesion. The CEB-fib [13] code provides an equation to estimate the bond strength of the concrete with smooth surfaces as a function of the concrete compressive strength, where:

$$u = 0.3\sqrt{fc'} \rightarrow fc' in\ MPa \quad (1)$$

Where u is the bond strength for the interface layer between the concrete and the sleeve and fc' is the characteristic concrete compressive strength. Using this equation a 14ksi grout will have a minimum cohesion strength of 427psi. In this article since the scope is to perform initial assessment for the concept of using splice sleeve and identify the potential areas for improvement for this connection, the authors decided to utilize the 50psi as a conservative value.

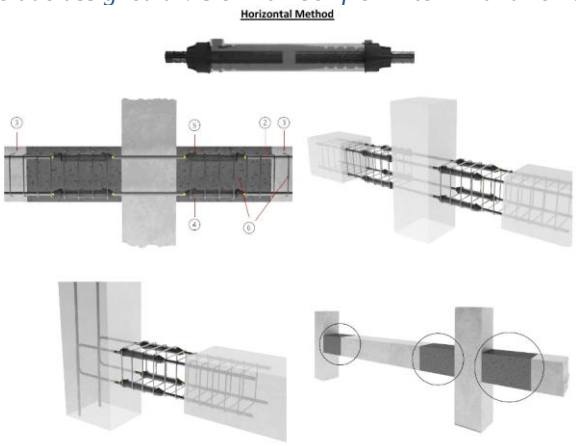
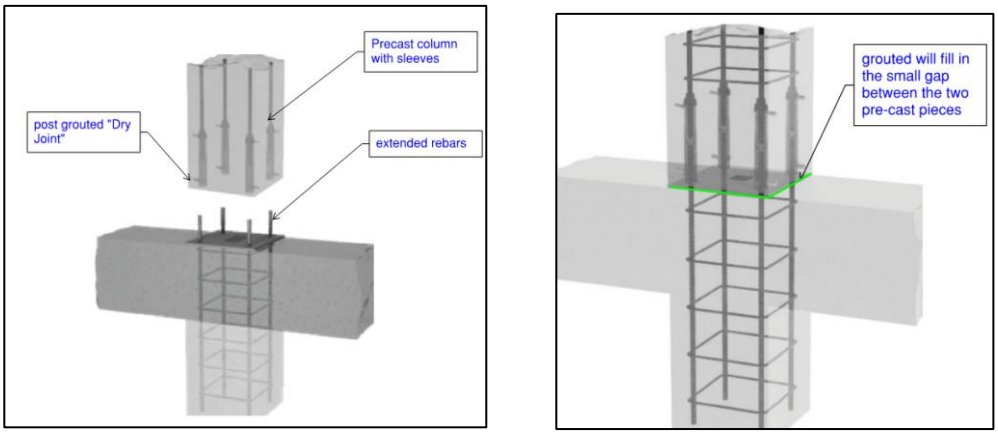


Figure 8. Wet Commissions using splice sleeves.



(a) (b)

Figure 9. Dry connections using splice sleeves (a) before installation (b) after installation and injection of grout

To model the dry connection, several changes were implemented to the CIP moment frame model. The model is presented in Figure 10, and the changes are:

1) The interface between the beam and the column is modelled using a 50 psi adhesive strength contact element.
2) The grout material is modelled using high-strength concrete properties
3) The link between the grout and the beam rebars is modelled using non-linear elastic springs. As previously discussed, the sleeve connection is classified as type 2 connection. This precludes the slippage between the sleeve and the rebar. However, the interface between the sleeve shell and the concrete will be based on the conventional concrete steel interface behaviour. The sleeves are made out of a relatively smooth steel type.

To model the slip force between the sleeve and the concrete CEB-fib [13] equation is used Equation(1). The value shown in this equation is limited to a maximum of 0.1mm (.004in) slippage. Using this equation the stiffness and the stiffness and the strength of the interaction between the sleeve and the concrete are calculated as follows:

$$F_{S-C} = \pi \cdot D \cdot L \cdot \left(u \cdot \frac{ksi}{mpa}\right) \rightarrow kips \quad (2)$$

$$K_{S-C} = \frac{F_{S-C}}{(0.004in)} \rightarrow kip/in \quad (3)$$

Where:

- $D \rightarrow$ is the sleeve diameter
- $L \rightarrow$ is the sleeve embedded length in the concrete
- $F_{S-C} \rightarrow$ is the slip critical force for the sleeve concrete interface region, and
- $K_{S-C} \rightarrow$ is the slip stiffness of the interface region, and

A non-linear spring is developed in the FEM to ties the sleeve with the concrete. The used sleeve for the precast connection is AW-11-NMB sleeve which has the following dimensions:

- D=3.5in
- L=18in

Accordingly the spring properties are calculated as:

$$F_{S-C} = \pi \cdot 3.5 \cdot 18 \cdot \left(0.3\sqrt{35.89} \cdot \frac{0.145\ ksi}{mpa}\right) = 51 kips \quad (4)$$

$$K_{S-C} = \frac{51}{(0.004in)} = 12750\ kip/in \quad (5)$$

The connection configuration after incorporating these changes is presented in Figure 10.

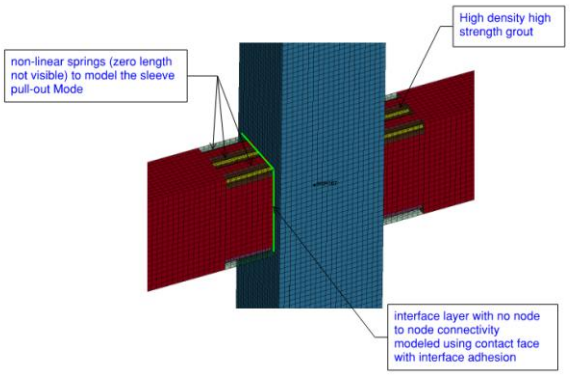


Figure 10. Precast Connection Configuration after incorporating the splice sleeve detailing.

The analysis was performed using the same input presented for the cast-in-place concrete, and the force-displacement relations were extracted and compared to the CIP model. The strength of the connection is reduced by 7%, which is considered a minor reduction in the system's performance. The primary issue is the drop in the connection ductility from 2.3% to 1.9%. This was expected since the shear performance of the moment frame connection is crucial for the connection ductility. The precast connection has smaller shear strength at the interface layer than CIP since the concrete strength is not credited, and only 50psi is considered at this interface layer.

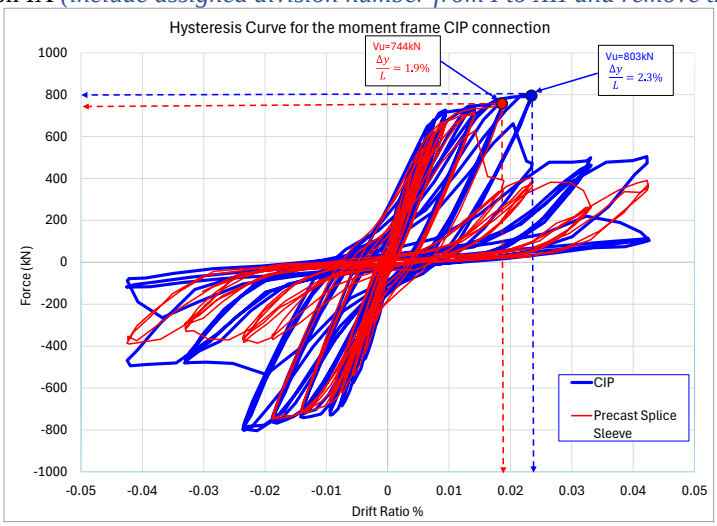
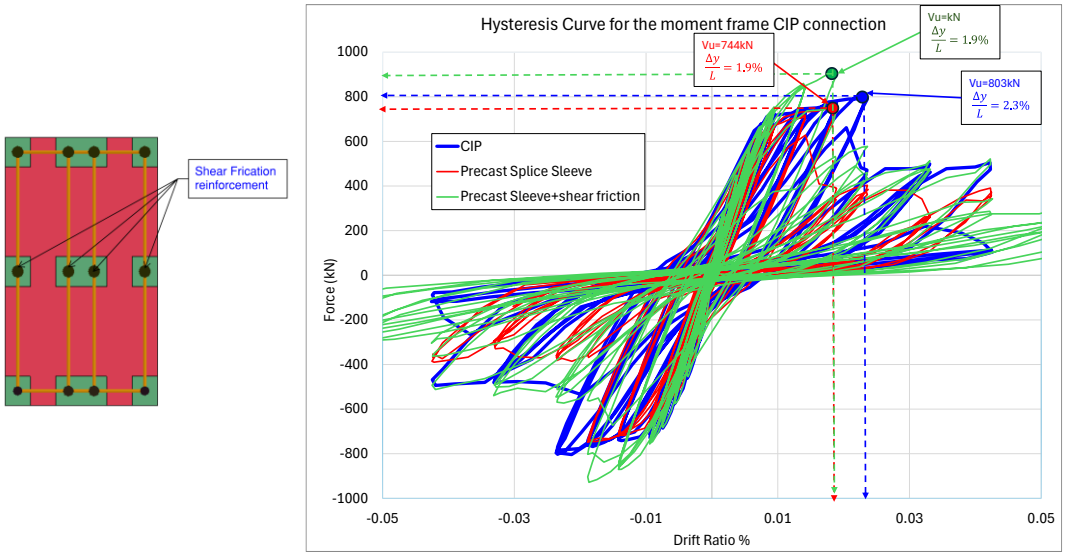


Figure 11. hysterics behaviour for the moment connection (CIP blue, Precast with sleeve red).

To explore if the performance of the connection can be enhanced by increasing the shear strength at the interface layer, shear friction rebars (4#11) are added through the centre of the section as presented in Figure 12 (a). Figure 12 (b) Present the force-displacement relation for the new connection. The strength of the joint increased by 20% (from 744kN to 910kN), but the ductility did not change. Further investigation is needed in this area.



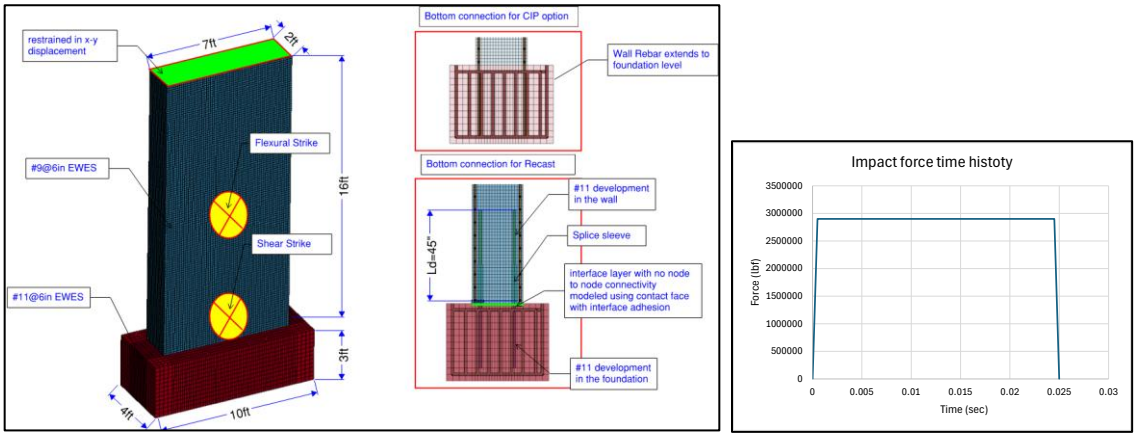
(a) (b)

Figure 12. Performance of the connection after including additional shear friction

PERFORMANCE OF SPLICE SLEEVE CONNECTION UNDER IMPACT LOADING.

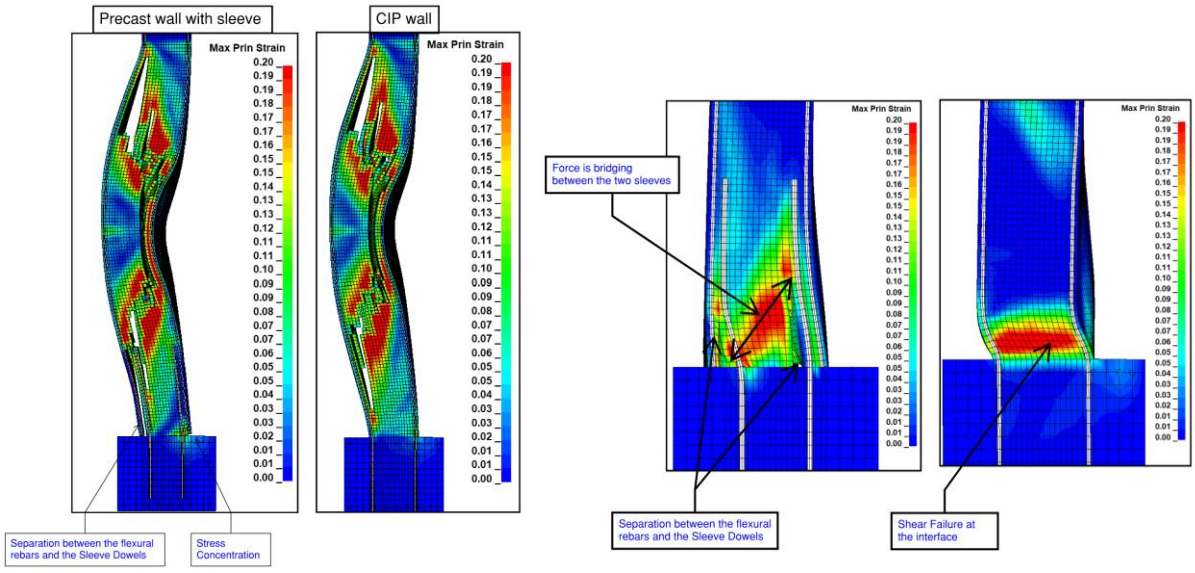
A full wall structure is investigated to assess the connection's performance under impact loads. The component used for the impact study is presented in Figure 13. Two strikes are studied: a flexural strike at the centre of the wall and a shear strike at the connection between the wall and the foundation. The impactor

consists of a water slug, which is 4ft wide and 8ft long. The weight of the slug is 7000lbs, impacting the wall at 328ft/s impact speed. Using the impulse of the projectile, the applied force time history to the wall is calculated, and the force time history is presented in Figure 13. This loading is based on the full-scale test done by Sandia National Lab fuel dispersion study [6].



(a) 3d FEM and connection detailing to foundation (b) applied force time history

Figure 13. A finite element model was developed for validation. (a) 3D model configuration (b) applied displacement.



(a) Flexural Strike (b) Shear strike

Figure 14. Impact analysis for CIP shear wall panel and precast shear wall panel with splice sleeve connection to the foundation

The results of the impact study are presented in Figure 14. The main observation from the two strikes is that in both cases, a major crack was developed between the wall #9 rebar and the #11 lap splice rebars. This indicates the need for stirrups around the sleeves and the #9 rebars to confine the reinforcement cage and prevent the separation between the rebars at this location. The wall connection, after incorporating this reinforcement, will be as presented in Figure 15.

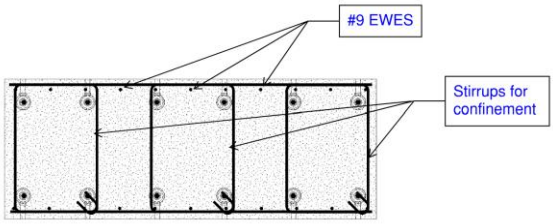


Figure 15. configuration of the wall after including the confinement reinforcement.

CONCLUSION

This paper evaluated precast concrete components for nuclear applications. It investigated the performance of a specific type of precast concrete connection, known as the splice sleeve grouted connection, for two different types of loading: Seismic Loading and impact loading. The results indicated that the selected connection has the potential to provide similar performance to cast-in-place concrete systems. Further work is needed to assess the shear capacity at the interface between the precast pieces to maintain the ductility of the system. Additionally, for impact resistance, additional reinforcement is needed to enhance the load transfer to the main precast wall reinforcement. Future work will emphasize these areas.

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