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Finite Element Modelling of Semi-Rigid Beam to Column Connection With Partly Hidden Corbel

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ABSTRACT
Utilizing many specimens in full-scaled experimental testing to study the behavior of precast concrete connections can be expensive. An alternative is to cast and carry out a minimal number of experimental tests and then model the connection/structure in a finite element software. The FE model can be validated using the few experimental tests carried out, and FEA can be used to analyze and study the behavior of the structure. Once validated, further parametric study can be carried out on the FE model. However, the modelling of precast concrete column-to-beam connection has not been explored widely by researchers. One of the main challenges is that modelling precast concrete connection involves complex surface to surface interaction and there is a lack of efficient ways on the modelling of the precast and in-situ concrete surface to surface interaction in finite element software. Hence, the main objective of this research is to model a hidden corbel precast beam-to-column connection in a finite element software, ABAQUS, which is then validated using previously published proposed precast connection and experimental works. Initially, the FE model was developed based on the technical drawings of the components and assembly of the precast connection. The FE model is validated when it can simulate similar structural behavior as the experimental tests. The behavior that were used for comparison with the experimental work is load–displacement and the failure cracks patterns' behavior. In general, the FE model results show similar behavior with the experimental results in regards to the load-displacement curve and failure cracks patterns.

Keywords—Finite Element Analysis, Beam to Column Connection Modelling, ABAQUS, Surface to Surface Interaction, Finite Element Modelling, Industrialized Building System

1. INTRODUCTION

The idea of Industrialized Building System (IBS) was introduced in the early 1600's when panelized timber houses were transported from England to the new settlements in North America. IBS is a construction system built by using prefabricated components; where component manufacturing is systematically performed using machinery, molds and other mechanical equipment. In Malaysia, Construction Industry Development Board (CIDB) has classified IBS into five (5) major categories which are Precast concrete framing, panel and box systems, Steel formwork systems, Steel framing systems, Prefabricated timber framing systems, and Blockwork systems [1]. Each connection and joints used for assembly of prefabricated elements into the structure are unique in every IBS. In general, the success of the IBS depends on the rigidity of the connections between the precast elements to ensure its resistance to the applied loads. In addition, the connection must also allow a simple and easy assembly to fasten the construction process [2]. Hence, the most important part of a precast concrete structure is a joint or a connection, particularly beam-to-column connection [3-4]. To study the behavior of precast connections, full scale experimental testing is required which can be quite costly. Hence, a popular alternative is to model the proposed structure in finite element software which utilizes Finite Element Analysis (FEA) to study the behavior of the structure. FEA is one of the most used technique in engineering analysis. FEA is a numerical method which helps solve complex problems in various fields such as, heat transfer, structural analysis, mass transport, fluid flow, electromagnetic potential and many more. In addition, FEA has been universally acknowledged to be used in structural design analysis. However, the structural behavior of the Finite Element (FE) model needs to be justified or validated through experimental testing to make sure that the structure modelled is accurately simulated to behave as the actual structure. Hence, through this method only limited or few experimental tests are needed to be carried out to validate the FE model and further parametric studies of the structure can be done. Therefore, in this paper, an FE model of the proposed precast connection by Mokhtar [5-6] is modelled in a finite element software, ABAQUS to carry out further parametric studies.

2. LITERATURE REVIEW

2.1. Beam-Column Modelling Approach

The modelling of reinforced concrete beam in ABAQUS is much simpler as compared to the modelling of precast concrete column to beam connection due to the additional modelling of the surface interaction in the precast concrete column to beam connection. The precast concrete column to beam connection involves complex surface to surface interaction between the precast concrete beam and precast concrete column or precast concrete and the in-situ concrete [7]. According to Feng *et al*. [7], there is a lack of efficient ways on modelling of the precast and in-situ concrete interface in finite element software. Feng *et al*. [7], in their study, modelled a double-sided beam to column connection to study the influence of precast and in-situ concrete interface, compression softening model, and bond slip under cyclic loading. It was suggested to use a 10 mm layer, with 90 percent compressive strength of the precast concrete, where the precast elements are jointed together using in-situ concrete. According to their study, the steel reinforcement was embedded in the concrete. The embedment function allows the bar to be fully bonded with the concrete. On the other hand, Magliulo *et al.* [8] presented a paper where they modelled the dowel bar in the concrete using cohesive surface interaction. The cohesive surface interaction uses the traction separation law. Tao *et al*. [9], in their study, modeled steel tube to concrete surface interaction using the coulomb friction model where the normal behavior was defined as hard contact and the tangential behavior was defined by friction coefficient of 0.6. Hence, depending on the interest of study different modelling techniques can be used to model steel to concrete surface interaction in finite element software. For concrete to concrete surface interaction, Nguyen & LİVAOĞLU [10] used coulomb friction model to model concrete to concrete surface interaction. The coulomb friction model is defined by the tangential behavior and the normal behavior. The cohesive surface interaction can also be used to model the concrete to concrete surface interaction, however, at the cost of complicating the model. Therefore, the Coulomb Friction model is usually preferred, and was adopted in this study.

2.2. Load – Displacement Relationship

The load-displacement characteristics help determine whether the behavior of connection is ductile or brittle. Structure should be capable of undergoing large deflections at near maximum load carrying capacity to show signs of failure when the structure is excessively being loaded. Therefore, a progressive collapse can be avoided [3]. Ductility allows a connection to experience large plastic deformations without any significant decrease of the force that is to be resisted [11]. The behavior of the connection determined through the load-displacement curve is shown in Fig. 1.

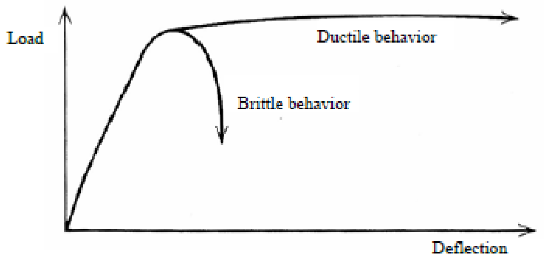


Fig 1. Typical load – displacement curve [12]

3. METHODOLOGY

3.1. Experimental Work

Mokhtar [5-6] carried out extensive experimental investigation on beam-to-column hidden corbel connection. The details of specimen and the experiments performed on the specimen are given in Table I and Fig. 2.

Table I. lab experiment overview [5-6]

Test reference	Connection	Loading Type	Connection Reinforcement Type
BHC1	Beam half joint with corbel	Reverse Load	T1
BHC2			T1
BHC3			T2

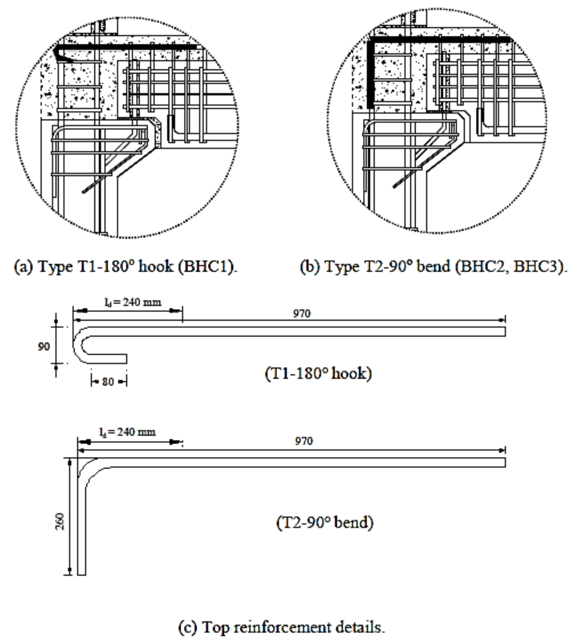


Fig 2. Detailing of tension reinforcement [5-6]

3.2. FE Modelling

The FE modelling procedure can be summarized in Fig. 3. Some assumptions were taken to model the corbel precast beam to column connection accurately and in an efficient method by limiting the surface to surface interactions in the model as shown in Fig. 4. The assumptions made are as follows:

1. The column precast concrete and in-situ concrete were modelled as one part but with their respective concrete compressive strength based on the experimental work done by Mokhtar [5-6].
2. The beam precast concrete and in-situ concrete were modelled as one part but with their respective concrete compressive strength based on the experimental work done by Mokhtar [5-6].
3. Between the column and the beam 10 mm layer of concrete with 50% compressive strength, 20 MPa, of the precast concrete was modelled based on research by Feng *et al*. [7].

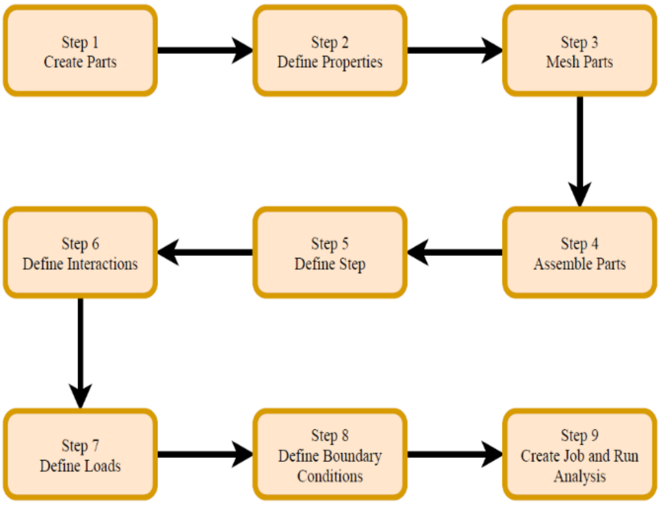


Fig 3. Modelling procedure

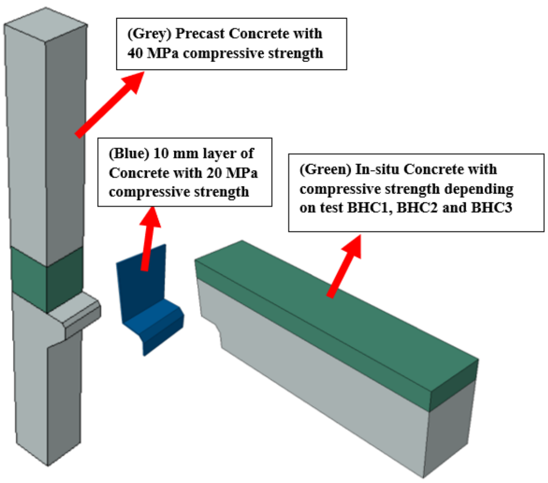


Fig 4. Modelling assumption illustration

3.3. Materials Properties

Concrete Damaged Plasticity Model (CDPM) accurately defines the structural behavior of reinforced concrete structures as it combines the effect of plastic behavior with damage in terms of stiffness reduction [13-15]. Steel behaves in a ductile manner and when broken it cannot reassemble. On the other hand, concrete behaves brittle but under stress reversal tensile cracks might close and reassemble. Hence, steel is better defined with plasticity and concrete with damage that is why CDPM accurately defines reinforced concrete behavior. The CDPM used in the model is based on the equations by Lubiner *et al.* [13] who proposed a triaxial yield function which was then modified by Lee and Fenves [16]. Lee and Fenves [16] modification took into consideration the different evolution of strength under tension and compression. The concrete stress, inelastic and damage relationship in compression and tension is based on the equations proposed by Aslani & Jowkarmeimandi, Carreira & Chu and Lubliner *et al.* [13-15]. Table II and Table III shows the mechanical properties of steel and concrete used in ABAQUS.

Table II. Mechanical properties of steel

Bar Type	f_y (MPa)	E_s (MPa)	Poission's ratio	Density (Tonne/mm^3)
Precast Main reinforcements	500	180000	0.3	7.85×10^{-9}
Links	250	180000	0.3	7.85×10^{-9}
BHC1 Tension Bar, T1	539.5	180000	0.3	7.85×10^{-9}
BHC2 Tension Bars, T1	592	180000	0.3	7.85×10^{-9}
BHC3 Tension Bars, T2	592	180000	0.3	7.85×10^{-9}

Table III. Mechanical properties of reinforced concrete

Parameter	Unit	Value
Density	Tonne/ mm^3	2.4×10^{-9}
Compressive Strength	MPa	40
Tensile Strength	MPa	4
Elastic Modulus	MPa	27897.52366
Poisson's Ratio		0.15
Eccentricity		0.1
Dilation Angle	°	56
Viscosity		0.01
K_c		0.667
$\frac{f_{b0}}{f_{c0}}$		1.16

3.3.1. Surface to Surface Interaction

The interaction between concrete to concrete surface is defined as surface to surface interaction with tangential behaviour and normal behaviour. The normal behaviour was defined using linear contact. It can also be defined as hard contact but sometimes due to sharp edges it can have convergence error causing the model to act more stiff. Hence, that is why linear contact was adopted. Tangential behaviour is defined based on the recommended values for concrete to concrete surface interaction by Nguyen & LİVAOĞLU [10]. The parameters defined for the tangential behaviour are shown in Table IV. The surface to surface interaction was applied between the column and the 10 mm layer of concrete. Similarly, the surface to surface interaction is also applied between the beam and the 10 mm layer of concrete. For steel and concrete interaction, the interaction embed is used to embed the steel in the concrete. Further details of the modeling can be found in [17].

Table IV. Tangential behaviour parameters

Friction coefficient	0.6
Shear stress limit	9
Fraction of characteristic surface dimensions	0.005
Elastic slip stiffness	11435

4. RESULTS AND DISCUSSION

4.1. Load – Displacement Results

The comparison of load – displacement relationship for LVDT 7 between the experimental results and simulated results are shown in Table V to VII and Fig. 6 for BHC1, BHC2 and BHC3. Fig. 5 shows the location of the applied load and LVDT 7. It can be observed that the FE model of BHC1, BHC2 and BHC3 accurately predicts the load – displacement relationship of the experimental specimens for LVDT 7. Hence, the experimental data validates the FE model of BHC1, BHC2 and BHC3 in terms of the load – displacement relationship in the beam. According to Farnoud *et al.* [18], the ductility factor is the ratio of the displacement at ultimate load to the displacement at the first yielding load. In addition, Wahjudi *et al.* [19] mentioned that the over-strength factor is the ratio of the ultimate load to the first yielding load. The over-strength factor and the ductility factor for the simulated results are higher than the experimental results due to the dilation angle in the CDPM taken as 56 ° which makes the FE model more ductile and causes the ultimate load to be higher.

Table V. Experimental ductility and over-strength factor results

Connec-tion	Yield load (kN)	Ultima-te Load (kN)	Displa-cemen-t at yield load (mm)	Displace-ment at ultimate load (mm)	Ducti-lity facto-r	Over-stren-gth factor
BHC1 (T1)	64.75	79.68	3.99	6.52	1.63	1.23
BHC2 (T1)	59.67	76.38	5.12	10.08	1.97	1.28
BHC3 (T2)	59.67	89.94	5.20	8.83	1.70	1.51

Table VI. simulated ductility and over-strength factor results

Conne-ction	Yield load (kN)	Ultima-te Load (kN)	Displa-cemen-t at yield load (mm)	Displace-ment at ultimate load (mm)	Ductil-ity factor	Over-stren-gth facto-r
BHC1 (T1)	55	85.74	3.4	7.31	2.15	1.56
BHC2 (T1)	57	91.74	3.5	7.65	2.19	1.61
BHC3 (T2)	57	96.54	3.2	8.69	2.72	1.69

Table VII. Experimental and simulated LVDT 7 displacement at ultimate load

Connection	Experiment-al, Ultimate Load (kN)	Experimental, LVDT 7 Displacement at ultimate Load (mm)	Simulated, Ultimate Load (kN)	Simulated, LVDT 7 Displacement at ultimate Load (mm)
BHC1 (T1)	79.68	6.52	85.74	7.31
BHC2 (T1)	76.38	10.08	91.74	7.65
BHC3 (T2)	89.94	8.83	96.54	8.69

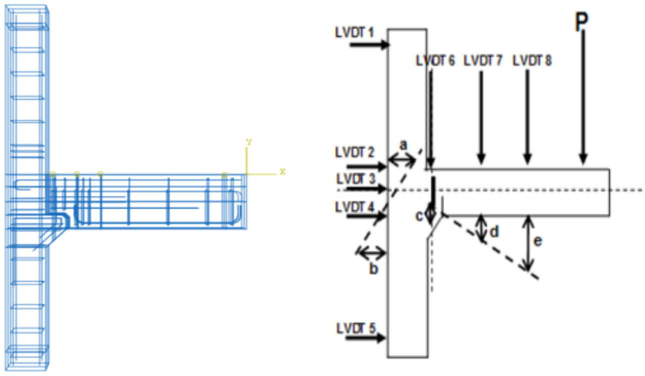


Fig 5. (a) Assembled parts in ABAQUS and (b) Location of LVDT 7 and loading point, P

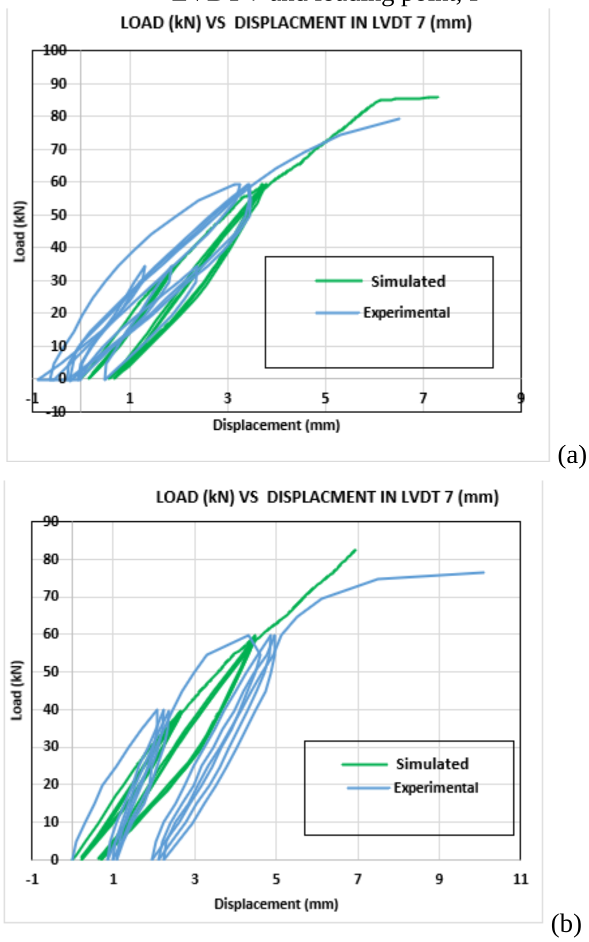
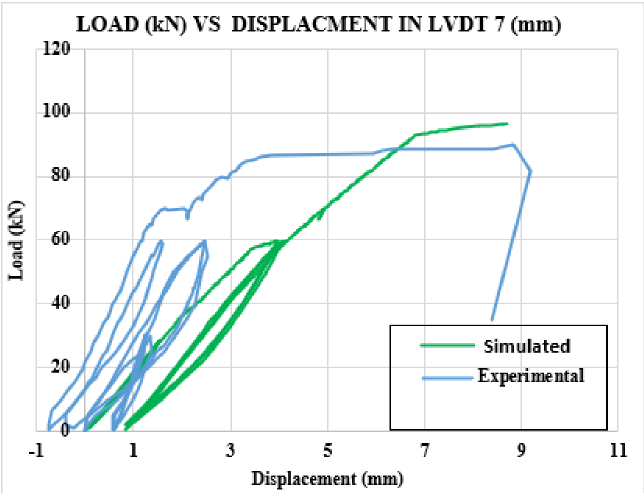


Fig 6. Load – displacement relationship at LVDT 7 for (a) BHC1, (b) BHC2 and (c) BHC3

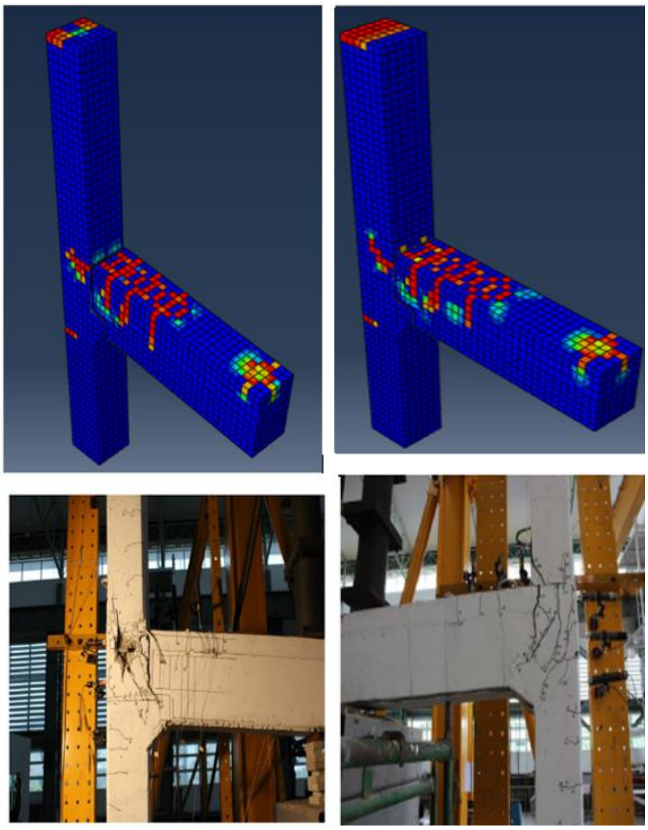


(c)

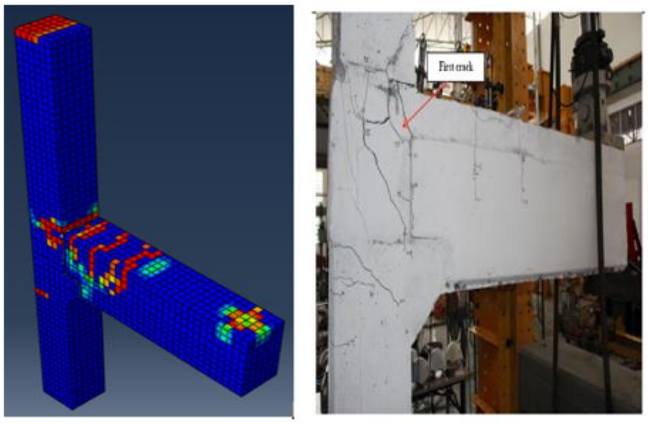
Fig 7. Load – displacement relationship at LVDT 7 for (a) BHC1, (b) BHC2 and (c) BHC3

4.2. Failure Crack Pattern Behaviour

The crack pattern during failure of the experimental specimens and simulated model are shown in Fig. 7 for BHC1, BHC2 and BHC3. The simulated FE models of BHC1, BHC2 and BHC3 have similar crack pattern to the experimental. It is important to note that the FE model does not accurately predict the crack pattern at the column. This may be due to the modelling assumptions made which resulted in lower column rotation. However, the crack pattern in the beam is quite accurately predicted by the FE models.



(a) (b)



(c)

Fig 8. Experimental and simulated failure crack pattern for (a) BHC1, (b) BHC2 and (c) BHC3

5. CONCLUSION

In this research, an FE model of precast beam to column connection with hidden corbel, was successfully developed in ABAQUS and validated using the experimental data (3 specimens, BHC1, BHC2 and BHC3) obtained from Mokhtar [5-6]. The precast beam-to-column connection was efficiently modelled with less surface to surface interactions and developed using a non-linear FE modelling in ABAQUS. The FE model was successfully validated using the load–displacement and the failure crack patterns from the experimental data determined by Mokhtar [5-6]. The comparisons show that the load-displacement curves and failure cracks patterns having high similarity in behavior between the FE model and the experimental result. For further study and to improve the accuracy of the FE model the following things are recommended:

1. Carry out simulation of the FE model with different dilation angle and compare the results.
2. Use a different CDPM for the FE model and compare to see the effect of different CDPM.

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