Finite Element Modelling of Interface Shear Strength at Concrete-to-Concrete Bond

Mazizah Ezdiani Mohammad[1,a*], Izni Syahrizal Ibrahim[1,b], and Redzuan Abdullah[1,c]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia

[a*]ezy11887@gmail.com, [b]iznisyahrizal@utm.my, [c]redzuan@utm.my

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Abstract. Interface shear strength between concrete layers cast at different times plays an important role to provide monolithic behavior of composite concrete. In this paper, a computational modeling approach is used to study the concrete-to-concrete bond behavior between two concrete layers cast at different times; concrete base and concrete topping. The compressive strength of the concrete base is 40 N/mm^2, while the concrete topping is 25 N/mm^2. Finite Element Analysis (FEA) package ABAQUS 6.12 is used to model the bond interaction of concrete-to-concrete layers, which is then verified with the experimental test. Four specimens with different types of surface textures are modeled; left "as-cast", indented, wire-brushing in transverse direction and projecting steel reinforcement crossing the interface. Failure of the bonded interfaces is modeled with cohesive zone model (CZM) approach with zero thickness interface element where the governing parameters are determined from the experimental "push-off" test results. Meanwhile, the projecting steel surface is modeled with Modified Drucker-Prager/Cap-Plasticity Model (CPM) approach with 1 mm thickness of interface element. The parameters used in the analysis include interface shear strength, fracture energy and elastic shear stiffness for CZM approach. The CPM parameters for modeling projecting steel surface are cohesion, interface friction angle, cap eccentricity parameter, initial cap yield surface position, flow stress ratio, yield stress at interface. The study shows that the difference between the modeled and experimental results is relatively small and therefore shows the capability of the finite element analysis to carry out interface analysis.

Introduction

In recent years, the use of composite concrete-to-concrete applied to the precast concrete and cast-in-place concrete topping has been increased due to ease of application in bridge and building constructions. A key part of this structure is by developing the composite action between the concrete layers in order for the structure to have monolithic behavior. Therefore, the behavior of concrete-to-concrete interfaces plays an important role to provide stiffer and stronger composite structure.

Design expressions of the interface shear strength in both Eurocode 2 [1] and CEB-FIB Model Code 2010 [2] considered the following parameters: concrete tensile strength, friction coefficient, concrete cohesion, steel reinforcement and normal stress at the interface. CEB-FIB Model Code 2010 [2] used a roughness parameter on the average roughness, R_a to quantify the strength of concrete-to-concrete bond, while Eurocode 2 [1] is based on qualitative assessment. Previous researchers [3, 4] proved that friction coefficient and concrete cohesion can be quantified by the roughness parameter. Santos et. al. [5] modeled a 2-dimensional specimen with steel crossing the interface and identified each of the following parameters: elastic shear stiffness, internal friction angle, dilatancy angle, cohesion fracture energy and bond slip relation between steel and concrete.

The study reported in this paper utilized a 3-dimensional finite element method to analyze composite concrete subjected to the "push-off" shear test to obtain the horizontal load-interface slip relationship. The modeling of concrete-to-concrete bond used Cohesive Zone Modeling (CZM) approach with zero thickness element for smooth or "left as-cast", indented and wire-brushing in transverse direction surface textures. The models are determined for the following three parameters:

(i) interface shear strength, (ii) elastic shear stiffness and (iii) fracture energy. On the other hand, the projecting steel crossing the interface is modeled using a continuum approach of Modified Drucker-Prager/Cap Plasticity Model (CPM) with 1 mm thickness of interface element. The modeling parameters are determined by cohesion, interface friction angle, cap eccentricity parameter, initial cap yield surface position, flow stress ratio, yield stress at interface and stress-strain steel reinforcement embedded in concrete.

The CZM approach is a traction-separation based modeling in which suitable for surface textures without steel as the bond failure between concrete-to-concrete exhibits brittle behavior with a sudden failure. Meanwhile, CPM approach is a continuum based modeling for modeling the projecting steel crossing the interface where the interface failure exhibits elastic-plastic behavior. A 3-dimensional model is used to analyze the interface bond behavior between the concrete layers. The models are analyzed without the applied normal stress (σ_n = 0 N/mm^2), which is known as pure shear models in this study.

The aim of this paper is to understand and clarifying the interpretation on the failure mechanism of concrete-to-concrete bond using analytical modelling. The results will then be verified with the experimental "push-off" test results.

Finite Element Models

In the following section, small-scale model for the "push-off" test is described in elements used such as continuum element, interface element and truss element.

Specimen Description

As in the experimental "push-off" test shown in Figure 1, concrete base with concrete topping is modeled in 3D Stress using FEA package ABAQUS 6.12 as shown in Figure 2. The dimension of the specimen is 300 × 300 × 100 mm for the concrete base and 300 × 300 × 75 mm for the concrete topping, which gives a total shear plane area of 90000 mm^2. The 3D stress model is chosen because it could give an accurate representation of the specimen in the experimental work by including the parameters of the interface shear failure. The model is analyzed using displacement control for better simulation with the experimental results.

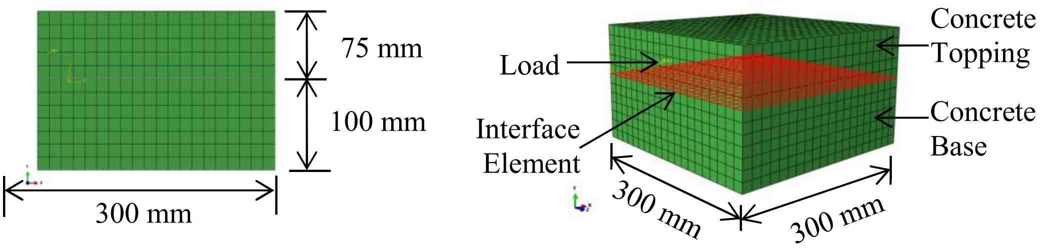
The FEA modeling properties for interface concrete with and without projecting steel are shown in Table 1 and 2. The Modulus of Elasticity for both concrete base and concrete topping are assumed according to Eurocode 2 [1]. 3-dimensional solid element of an 8-node linear brick (hexahedral), reduced integration and hourglass control, C3D8R for smooth and projecting steel surfaces and a 6-node linear triangular prism, C3D6 for indented and wire-brushing in transverse direction surfaces are used in the model.

The interface shear strength is modeled with interface element to connect the two surfaces of the concrete layers. A zero-thickness interface element is embedded in the model via shared nodes or tie constraints to connect the concrete base and concrete topping [5-9]. The 3-dimensional interface element used in the analysis is COH3D8.

To evaluate the influence of interface shear strength and stiffness on the interface shear failure for different surface textures, four sets of interface shear-slip curves from experimental test were examined. The variations on the surface geometry depend on the surface textures at the interface. Four (4) types of surface textures are modeled which includes smooth or left "as-cast", indented, wire-brushing in transverse way and projecting steel crossing the interface.

The surface with the projecting steel is modeled to an elastic-plastic behavior. This is based on the observation made in the experimental test where there is sufficient ductility behavior at the interface. Therefore, the interface is modeled with 1 mm thickness of interface element with continuum approach and the projecting steel is modeled as linear truss element that can carry tensile and compressive loads.

Figure 1 "Push-off" test setup



(a) (b)

Figure 2 "Push-off" FEA model

Table 1 FEA modeling properties for interface without the projecting steel

Item	Assumption
Mode of analysis	ABAQUS/Standard
Surface element type (smooth surface)	Hexahedral C3D8R (Continuum 8 node linear brick, reduced integration, hourglass control)
Specimen element type (indented and transverse roughened surfaces)	C3D6 (Continuum 6 node linear triangular prism)
Interface element	COH3D8
Constitutive model	Cohesive Zone Model (CZM)
Modeling steps	3 steps +1 initial

Table 2 FEA modeling properties for interface with the projecting steel

Item	Assumption
Mode of analysis	ABAQUS/Standard
Surface element type	Hexahedral C3D8R (Continuum 8 node linear brick, reduced integration,hourglass control)
Truss element	T3D2 (A 2-node linear 3D truss)
Interface element	COH3D8
Constitutive model	Modified Drucker-Prager/Cap Model
Modeling steps	3 steps +1 initial

Material Behavior

Table 3 shows the concrete properties used for the concrete base and concrete topping, while the steel properties for the projecting steel is shown in Table 4. The average stress-strain curve from theoretical of Wang and Hsu steel model [10] for the 6 mm diameter mild steel bar embedded in concrete is shown in Figure 2.

Table 3 Concrete properties

Concrete Properties	Value
Elastic Modulus	35 GPa (Concrete Base) 30GPa (Concrete Topping)
Poisson ratio	0.20 (Concrete Topping) 0.17 (Concrete Base)

Table 4 Steel R6 properties

Steel Properties	Value
Elastic Modulus	209 GPa
Yield stress	250 MPa

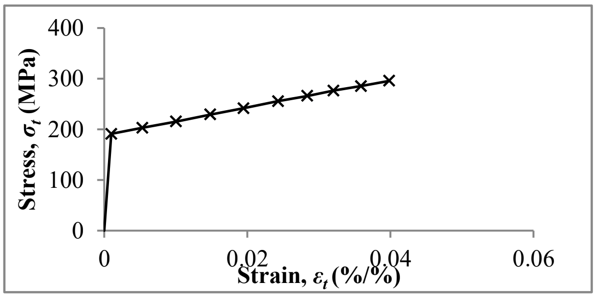


Figure 2 Theoretical tensile stress-strain relationships for 6 mm diameter mild steel bar using Wang and Hsu [10] model

Interface Element Behavior

Interface element plays an important role to predict the interface shear strength of concrete-to-concrete bond. In this study, the model comprises two interface failure behaviors, which are brittle-cracking and ductile. Therefore, two different types of interface behavior are applied using the traction-separation approach, which is (i) Cohesive Zone Modeling (CZM), and (ii) Modified Drucker-Prager/Cap-Plasticity model (CPM). Both approaches are represented as linear pressure dependent where the interface element is modeled with continuum approach.

Cohesive Zone Modeling (CZM)

The CZM includes a constitutive relation between the traction, τ acting on the interface and the corresponding interface separation, δ (displacement or slip at the interface). Traction separation law is applied as shown in Figure 3 where it is typically characterized by the interface shear strength, N and fracture energy, GTC. The area under the traction-separation curve shows the fracture energy, GTC. Linear elasticity with damage analysis is available in both ABAQUS/Standard and ABAQUS/Explicit. Modeling of damage analysis under the general framework is a) damage initiation, b) damage evolution, and c) removal of elements. From the experimental results, the critical fracture energy can be extracted using the following expression:

$$G_{TC} = \frac{1}{2} \times N \times \delta \times 1000 \quad (1)$$

where N is the load (N) and δ the displacement (mm).

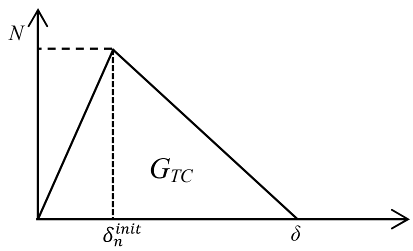


Figure 3 Typical traction-separation approaches

Since the interface element is zero-thickness, the cohesive section properties thickness, h_{eff} is taken as 1. The Elastic Modulus of the traction separation law is interpreted as penalty stiffness. The stiffness that relates interface shear strength to displacement is given as:

$$K_n = N_{max}/\delta_n^{init} \quad (2)$$

Modified Drucker-Prager/Cap Plasticity Model

The model is assumed to be isotropic and its yield surface of the modified Drucker-Prager/Cap Plasticity model comprises of three parts (see Figure 4), which is (i) Drucker-Prager shear failure surface, (ii) elliptical cap, which intersects the mean effective stress axis at a right angle, and (iii) smooth transition region between the shear failure surface and the cap. The properties values for projecting steel surface are shown in Table 5.

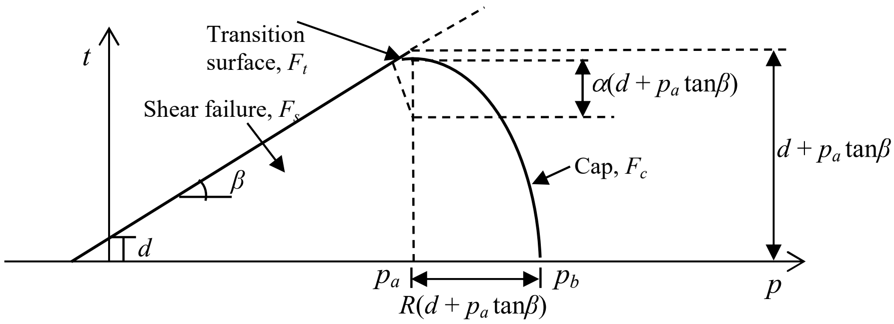


Figure 4 Yield surfaces of the modified cap model in the *p*-*t* plane

Table 5 Cap Plasticity concrete model parameters

Parameter	Value
Material cohesion, c (MPa)	0.71
Material angle of friction, β (degree)	41
Cap eccentricity parameter, R	0.1
Initial cap yield surface position	0
Flow stress ratio	1
Cap hardening	Yield stress: 2.06, strain: 0

Results and Discussion

The FE model is applied with horizontal load until the two concrete layers slide relative to each other. The loading position and model setup are the same to that of the experimental test. For each parameter, the main output from the analysis is the horizontal load and interface slip.

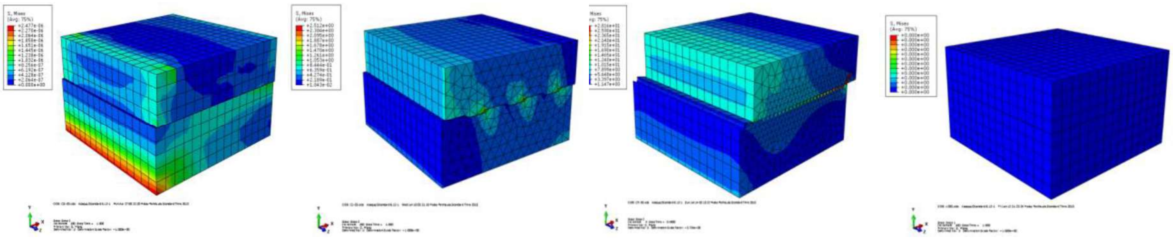
Four different surface textures with a total of 16 models of the horizontal load–interface slip curves from experimental "push-off" test results were evaluated for the modeling of the interface elements. These experimental curves are used to define the properties of the interface elements in the FEA model.

Stress Distribution

The deformed shape for the smooth or left "as-cast" surface of the composite is presented at interface shear failure as shown in Figure 5 and 6. Failure occurred along the interface after both concrete layers slide and become separated. The horizontal load-interface slip relationship from the FEA for each surface texture is shown in Figure 7 and compared with the experimental test results. The differences between the FEA and experimental results are relatively small for each surface texture, where: (a) smooth or "left as-cast" at 0.01%, (b) indented at 2.00%, (c) transverse roughened at 0.04%, and (d) projecting steel at 3.74%.

The smooth or left "as-cast", indented and transverse roughened surfaces show the traction-separation behavior at the interface. The CZM approach is suitable for modeling with brittle behavior, which is the same case for the concrete-to-concrete bond without the projecting steel. The crack initiation point occurs at ultimate horizontal load before the sudden failure at interface which breaks apart the concrete layers.

However, for the surface with projecting steel as shown in Figure 7(d), the FEA model relationship exhibits an elastic-plastic behavior. After the transition from elasticity to plasticity, the interface behavior is in perfectly plastic behavior. The interface behavior in this model is assumed to be hardening after the failure of the interface bond. This is because the hardening takes place by the projecting steel. Therefore, the stress contour in Figure 5(d) is not visible as the projecting steel takes the stress after the failure of the interface bond. The visibility of the stress contour at the projecting steel is shown in Figure 6.



(a) (b) (c) (d)

Figure 5 Stress distribution of the "push-off" model: (a) smooth or "left as-cast" surface, (b) indented surface, (c) transverse roughened surface, and (d) surface with projecting steel

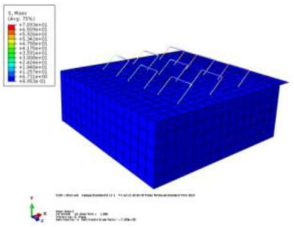
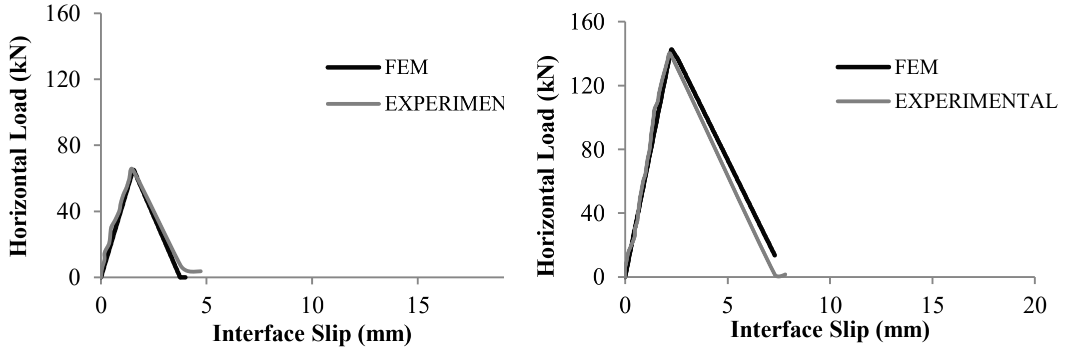
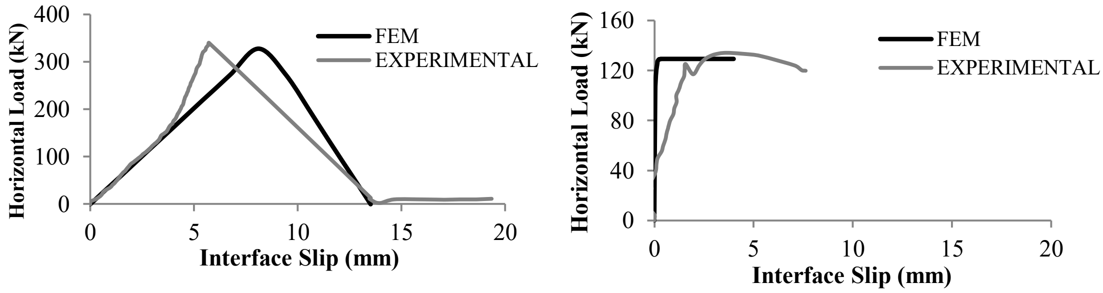


Figure 6 Projecting steel taking the interface shear stress after the failure of the interface bond



(a) (b)



(c) (d)

Figure 7 Horizontal load-interface slip relationships: (a) smooth or "left as-cast" surface, (b) indented surface, (c) transverse roughened surface, and (d) surface with projecting steel

Interface Shear Stress Distribution

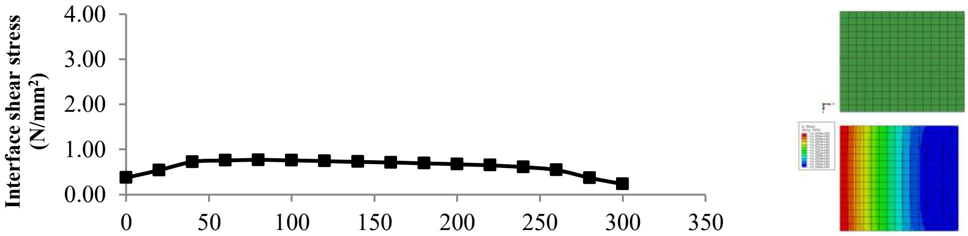
The changes of the interface shear stress distribution along the length of the interface element are shown in Figure 8. The interface shear stress distribution is plotted from the node at the middle of the interface element. All stress distributions are plotted at ultimate load for each of the surface texture.

The maximum stress for the smooth or left "as-cast" surface occurred at the edge in the vicinity of the crack tip in front of the loading point as shown in Figure 8(a). These nodes are at higher stress, which causes slipping between the interfaces. After undergone higher stress at the point where the crack initiated, the stresses started to decrease in which the crack propagated along the interface. As the stress goes beyond in the cohesive region and under the fracture region, sudden failure of the interface bond occurred.

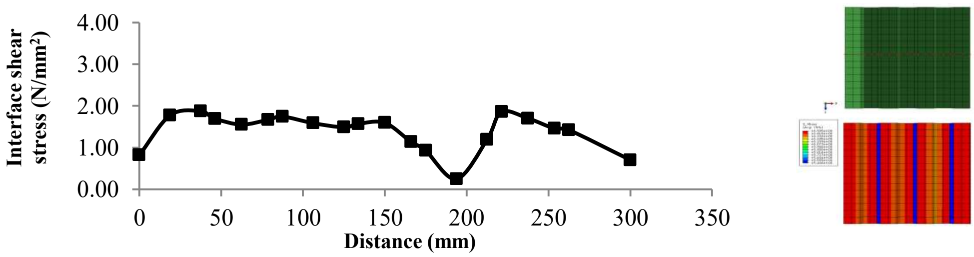
In Figure 8(b), the interface shear stress distribution of the indented surface first increases until it reached higher shear stress. Since the surface is irregular, the stress increases and decreases alternately. This shows that after the 200 mm length, the stress increases until at the highest point for the complete crack propagation at the interface.

The transverse roughened surface is irregular small since it is roughened by wire-brushing. Therefore, the stress increases and decreases alternately as shown in Figure 8(c). This shows that after the 285 mm distance, the stress increases at the highest point for the complete crack propagation at the interface. At this point, the resistance from the rough surface at the end of crack tip causes higher stress in order to break apart the concrete layers.

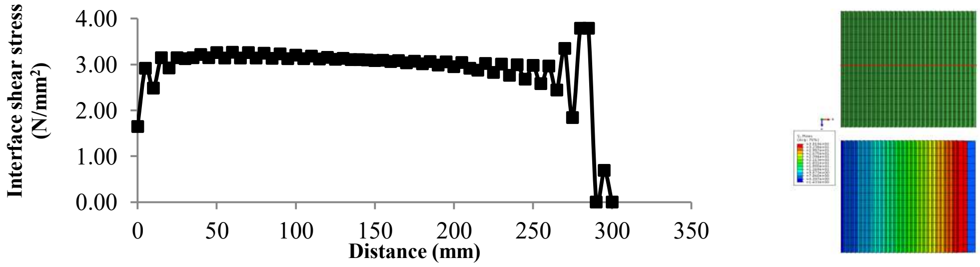
For the surface with projecting steel shown in Figure 8(d) the interface shear stress decreases and increases in an ascending manner until the 200 mm distance. After this distance, the stresses are maintained at the end of crack tip. At this point the stresses are then transferred to the projecting steel as the interface bond is broken.



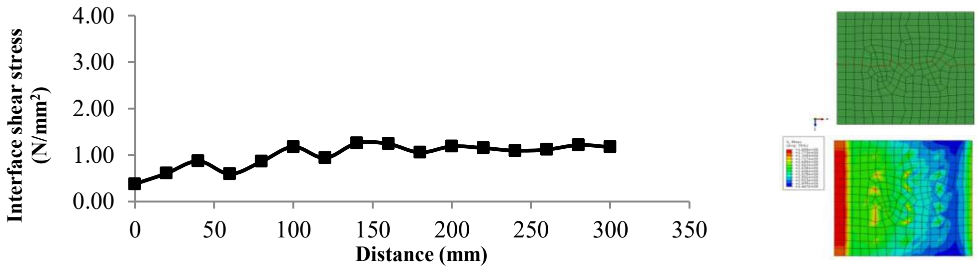
(a)



(b)



(c)



(d)

Figure 8 Interface shear stress distributions along the interface at: (a) smooth or "left as-cast" surface, (b) indented surface, (c) transverse roughened surface, and (d) surface with projecting steel.

Conclusion

FEA package using ABAQUS/Standard was used to model and analyze analytically the interface shear strength and the stress distribution by adopting the "push-off" test method as in the experimental test. The aim of the study is to understand and clarifying the interpretation on the failure mechanism of concrete-to-concrete bond using analytical modeling. The findings from the study can be concluded as follows:

a) The concrete-to-concrete bond is modeled using the CZM approach at the interface concrete without the projecting steel, while the CPM approach for the interface concrete with the projecting steel.

b) The stress contour of the interface shear failure and interface shear stress distributions at ultimate load show are analyzed on different surface textures.

c) The results of the FEA model and experimental results meet an agreement with less percentage differences.

d) The model and analysis procedure can be used to predict the behavior of composite concrete layer cast at different times with and without the projecting steel.

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Numerical Prediction of Cantilevered Reinforced Concrete Wall Subjected to Blast Load

Nasly Mohamed Ali[1,a], Sharifah Maszura Syed Mohsin[1,b], Mazlan Abu Seman[1,c*] and Zainorizuan Mohd Jaini[2,d]

[1]Faculty of Civil Engineering & Earth Resources, University Malaysia Pahang, Malaysia

[2]Jamilus Research Centre, University Tun Hussein Onn Malaysia, Malaysia

[a]nasly@ump.edu.my, [b]maszura@ump.edu.my, [c*]mazlan@hotmail.co.uk, [d]rizuan@uthm.edu.my

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Abstract. Aggressor attack using improvised explosive not the only source for blast load. Some commercial equipment and daily activities can contribute as well, such as electrical transformers, gas pipelines and industrial plants. Normally, reinforced concrete wall is used as the protection. Therefore, it is vital to estimate the structure damage. In this paper, the behaviour of cantilevered reinforced concrete (RC) wall subjected to blast load is investigated through numerical simulation. A three-dimensional solid model, including explosive, air and RC wall is simulated. The wall has a cross-sectional dimension of 1829 mm × 1219 mm with wall thickness of 152 mm and 305 mm thickness of strip footing. It is subjected to 13.61 kg Trinitrotoluene (TNT) explosive at 1.21 m standoff distance from the centre. Concrete and steel material model behaviour considers the high strain rate effect and dynamic loading. The Arbitrary Langrange Euler (ALE) coupling interface between air and solid are applied to simulate the damage mechanism of RC wall. A Comparison between experimental data on blast pressure and damage pattern shows a favourable agreement. The numerical result shows, the displacement-time history on each side is in a contrary direction. A permanent deformation is occurred and, the blast pressure near to the wall base is the highest.

Introduction

Study on the structure with the capable of withstanding blast load in the construction industry around the world became important since the last decade due to the September 11, 2001 attacks in New York. Besides the terror attacks and other acts of war, accidental explosions due to civilian accident and commercial equipment occurring in urban areas or close to facilities such as building and protective structures may cause tremendous damage and loss of life. Due to space constraint, residential homes, commercial and utilities building are developed just next to traffic access such as road, highway and railways in the most major cities. Those mentioned situations are prone to dynamic loading due to transformer explosion, vehicle and train accident. As one of the effective approaches, barrier walls can be constructed to ensure the safety of civilian. Experimental and numerical analysis have demonstrated that a barrier wall can effectively protect nearby building from external explosion [1]–[3].

RC is widely used as the principal construction material for urban environment, infrastructure or as different types of civilian and military facilities. Generally, plain concrete is known to have a relatively high blast resistance compared to other construction material. However, the plain concrete of higher strength will lead to a more brittle failure compared to ordinary concrete. Therefore the combination of using proper amount of steel reinforcement and the right concrete strength will result a ductile concrete, hence limit the structural damage in RC structural element. Series of the experimental and numerical have been conducted to investigate the damage due to blast load in different scope of works. The investigation lead to the scope for strengthening the strength of ordinary reinforced concrete structure with different method such as retrofitted the concrete material with steel fiber [4]–[7]; replaced the normal strength steel with enamel coated steel [8] or retrofit the structure with different material such as aluminium foam [9]. However, in the attention to strengthen the reinforced concrete, some of the experimental test show a mixed result or worse than