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Numerical Analysis of Splitting Tensile Strength of Steel Fibre Reinforced Concrete under Static Loading

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Abstract: This paper presents the study on the numerical analysis of splitting tensile strength test of steel fibre reinforced concrete under static loading. ABAQUS FEM software is used to model the test configuration for plain concrete and steel fibre reinforced concrete (SFRC) based on the experimental investigations that studied the effectiveness of adding steel fibres of 1.5% volume fraction into the concrete mix. Four 3D models are created which are brick concrete, brick SFRC, stone concrete and stone SFRC. The numerical analysis results are compared with the published experimental results in terms of splitting tensile strength, tensile stress-strain relationship and tensile damage. The splitting tensile strengths from horizontal stress output are found to be slightly lower compared to the experimental results with percentage difference of less than 15%. While the results from using analytical formula also underestimate the splitting tensile strength with percentage difference up to 22% when compared to the experimental results. Elastic modulus from tensile experimental results should be taken as Young's modulus of the model since it gives results that are closer to experimental results. The Poisson's ratio that gives the closest results to the experimental result is taken as the Poisson's ratio of the concrete and SFRC. The adopted 3D model captured reasonably well the reaction of the concrete cylinders subjected to splitting tensile test. Numerical analysis displays a strong correlation with the experimental results after proper evaluations and realistic optimizations of the governing parameters through extensive analyses.

Keywords: Numerical analysis, splitting tensile strength, Steel Fibre Reinforced Concrete (SFRC), Concrete Damage Plasticity Model (CDPM)

1. Introduction

Concrete is widely used in building and civil engineering field due to its economic value, flexibility, strength and durability. Concrete is strong in compressive strength but low in tensile strength due to its brittle nature. This weak in tensile strength has been of the main weakness for its practical application. Hence, much research has been done on

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addition of fibres to remedy its brittleness by changing it from brittle to ductile also increasing its tensile strength in order to enhance the robustness, toughness and durability of engineering structures. Steel fibre reinforced concrete (SFRC) also has been applied widely as one of the method to increase the performance and capacity of concrete.

Therefore, to investigate the effects of addition of steel fibres into the normal concrete on its mechanical properties especially tensile strength, splitting tensile test need to be carried out on both plain concrete and steel fibre reinforced concrete. Tensile strength of concrete is focussed in this study because it is one of the basic and important properties which greatly affect the extent and size of cracking in structures. Concrete develops cracks when tensile forces exceed its tensile strength. So, it is necessary to determine the tensile strength of concrete to determine the load at which the concrete members may crack. Furthermore, according to [5], at the post-cracking stage, the load carrying capacity of steel fibre reinforced concrete (SFRC) has made it a point of interest in modern researches.

Even though many experimental researches have been done successfully to study the effect of steel fibre addition into concrete, it is just not enough to only get results from the experiments due to financial and time constraint [11]. Hence, with current computational facilities and knowledge on computational modelling, finite element modelling can be very useful to investigate this. From the literature review also, it is observed that numerical analysis studies on the splitting tensile behaviour of steel fibre reinforced concrete are very limited. Not many researchers study the splitting tensile stress-strain behaviour therefore making this study quite challenging. Most studies presented the results from splitting tensile strength test in terms of maximum splitting tensile strength only and not in stress-strain relationship.

Therefore, a published paper by [5] is chosen for this study as benchmarking because the experimental splitting tensile stress-strain results for both plain concrete and steel fibre reinforced concrete are presented. In the study by [5], 1.5% volume fraction of customized steel fibres are incorporated into brick concrete and stone concrete to determine its effectiveness in improving the tensile strength and failure behaviour. Therefore, this report aims to conduct study on the simulation of splitting tensile strength test of steel fibre reinforced concrete using the ABAQUS finite element modelling software. The parameters that govern the simulation of this splitting tensile strength test will be identified in order to give results that can predict the experimental result. Accordingly, this study will simulate splitting tensile strength test on four models which are brick concrete, stone concrete, brick steel fibre reinforced concrete and stone steel fibre reinforced concrete.

2. Methodology

2.1 Structural Idealization and Analysis Assumptions

The idealization method used for this numerical modelling of splitting tensile strength of steel fibre reinforced concrete is by using 3D element created with solid shape. This model will consist of concrete cylinder, plywood loading strip and steel plate. The concrete cylinder and plywood loading strip were assigned as deformable type of solid while loading plate will be assigned as discrete rigid solid which does not account for deformation. In ABAQUS, several methods to model the materials are available and already provided as part of the features. Among the available methods to analyze concrete behavior are concrete smeared cracking and concrete damaged plasticity (CDP) model. As mentioned previously in the literature review, according to [8], the Concrete Damage Plasticity Model (CDPM) is suitable for both nonlinear compressive and tensile behaviours. Hence for this study, the Concrete Damage Plasticity Model (CDPM) in ABAQUS is used, assuming that fibres were uniformly distributed in the matrix and the steel fibre reinforced concrete is thus modelled as a homogeneous material.

2.2 Defining Geometry

The model consisted two steel plates, two plywood loading strips and a concrete cylinder. The steel plates and the plywood loading strips were modelled with 4-node shell elements with reduced integration (S4R). The steel is modeled as an elastic material with Young's modulus of 210 GPa and Poisson's ration of 0.3. As for the plywood, the material properties were defined with elastic modulus of 8000 MPa, Poisson's ratio of 0.3 and yield strength of 15.58 MPa. According to [10], the C3D8R elements are often used to prepare concrete models. Therefore, the concrete cylinder is modelled as C3D8R which also described as 8-node linear hexahedral element with reduced integration. The dimension of the concrete cylinder is as the experimental test with dimension of 100mm width and 200mm length. As for the loading strip, it is in 25 mm width as and 3 mm depth as per [3] C496/C496M-17. Once all the parts were created, they were assembled as the configuration assembly in the experiment. Partitions were created to all parts in order to provide better mesh distributions especially for concrete cylinder part. Partitions were all created symmetrically to all the parts. Fig. 1 shows the assembly of the splitting tensile test used in the simulation for all concrete models.

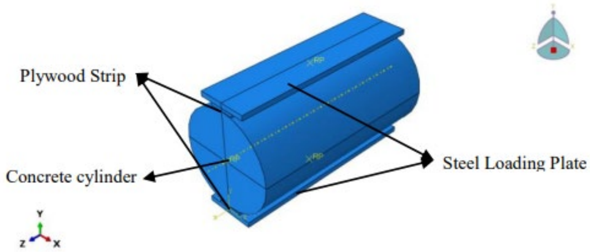

Fig. 1 - Model assembly of splitting tensile test

2.3 Defining Material Properties

In order to simulate the splitting tensile test on all four samples namely brick concrete, stone concrete, brick steel fibre reinforced concrete and stone steel fibre reinforced concrete in ABAQUS platform, it is important to have the following characteristics, i.e. (i) elastic modulus, (ii) compressive stress-strain relationship, (iii) ultimate uniaxial tensile strength, and (iv) the Poisson's ratio. Furthermore, in concrete damage plasticity model, there are five other parameters that are required to be defined which are the dilation angle in degrees, the flow potential eccentricity, the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress, the viscosity parameter and the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian. The reference values for the above-mentioned parameters of finite element analysis have been provided by numerous researchers. Table 1 includes the constitutive parameters of Concrete Damage Plasticity Model (CDPM).

Table 1 - The constitutive parameters of Concrete Damage Plasticity Model (CDPM)

Parameter	Symbol	Adopted value in ABAQUS	Sources
Dilation angle	ψ	40	[1]
Flow potential eccentricity	ϵ	0.1	Default
The ratio of initial equibiaxial compressive strength to initial uniaxial compressive strength	f_{b0}/f_{c0}	1.16	Default
The ratio of the second stress invariant to the tensile meridian	K_c	0.667	Default
Viscosity parameter	μ	0.01	[6]

The compressive and tensile stress-strain data to be used in the numerical analysis are from the experimental data provided by [5] as shown in fig. 2 and fig. 3.

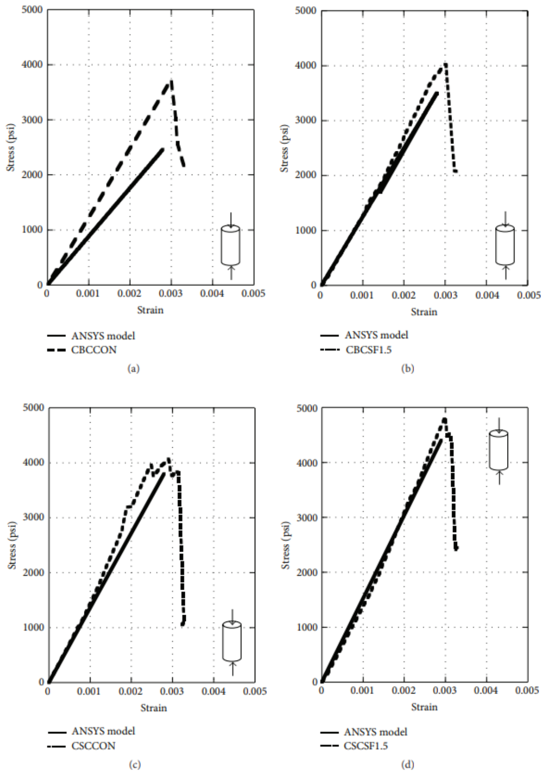

Fig. 2 - Compressive stress-strain relationship from experimental tests and numerical analyses: (a) brick concrete; (b) brick SFRC; (c) stone concrete; and (d) stone SFRC [5]

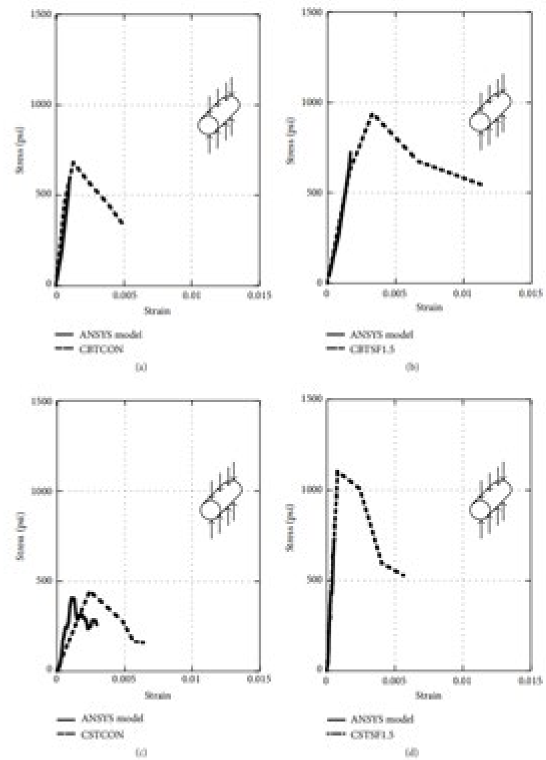

Fig. 3 - Tensile stress-strain relationship from experimental tests and numerical analyses: (a) brick concrete; (b) brick SFRC; (c) stone concrete; and (d) stone SFRC [5]

Then, after compression and tensile stress-strain curve data are obtained, it is required to determine the inelastic strain and cracking strain to be inserted as properties in ABAQUS Concrete Damage Plasticity Model. Inelastic compressive strain is calculated as follows:

$$\varepsilon_c^{in}=\varepsilon_c-\varepsilon_c^{el} \quad (1)$$

where:
ε_c = Total compressive strain
ε_c^{el} = Elastic compressive strain

$$\varepsilon_c^{el}=\sigma_c/E_0 \quad (2)$$

where:
σ_c = Stress for uniaxial compression, MPa
E_0 = Initial undamaged modulus, MPa

Next is for the concrete tension stiffening properties in which the data are required in terms of cracking strain. The cracking strain is defined as the total strain minus the elastic strain corresponding to the undamaged material:

$$\varepsilon_t^{ck}=\varepsilon_t-\varepsilon_t^{el} \quad (3)$$

$$\varepsilon_t^{el}=\sigma_t/E_0 \quad (4)$$

where:
ε_t = Total tensile strain
ε_t^{el} = Elastic tensile strain
σ_t = Stress for tension, MPa
E_0 = Initial undamaged modulus, MPa

The tension damage is also one of the interests of this research, hence its tension damage parameter is included in the tensile damage sub option for the Concrete Damage Plasticity model. The tension damage parameter, d_t could be expressed as follow:

$$d_t=1-\sigma_t/\sigma_{t0} \quad (5)$$

where:
σ_t = Tensile stress, MPa
σ_{t0} = Maximum tensile stress, MPa

2.4 Defining Boundary Condition, Interaction and Loading

Loading and boundary condition are applied as they are tested experimentally. According to [5], the loading for this model is applied as displacement boundary condition as the experimental testing is done followed by displacement control testing procedure at a rate of 0.5 mm/min. The displacement is applied to the upper steel plate to move it down. Surface-to-surface “hard” contact and friction are defined between the loading strip and the upper and lower surfaces of the concrete cylinder. The friction coefficient is taken as 0.62.

2.5 Output Process

The outputs required for this study are horizontal stress distribution, vertical reaction force, horizontal displacement and tensile damage of the splitting tensile test model. The horizontal stress which is in x-direction will indicate the tensile stress in the model. The vertical reaction force is required to be used in the splitting tensile strength equation provided by [13] as shown in Equation 6:

$$\sigma_{xx}=2P/\pi D \quad (6)$$

where:
σ_{xx} = Horizontal normal stress, MPa
D = The specimen diameter, mm
P = The load per unit thickness, N/mm

The horizontal displacement is required to measure the strain and while the tensile damage output is required to display the tensile damage in the model. The main reference to obtain the output is from the illustrations by [7] in which the tensile stress is measured in the centre line of the concrete cylinder and strain are measured from the location of Linear Variable Displacement Transducers (LVDTs) as depicted in Figure 4.

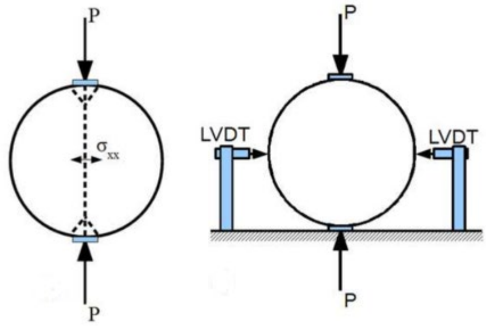

Fig. 4 - Test configurations of splitting tensile strength test [7]

As for the strain, it is obtained from the displacement output by calculating the change in displacement at two points over its original diameter. The strain is calculated from:

$$\varepsilon = \Delta b / b \quad (7)$$

where:
Δb = Relative horizontal displacement, mm
b = Length of the diameter, mm

After stress and strain data are obtained, stress-strain curve can be plotted to be validated with experimental results. As for the tensile damage output, it can be directly displayed from the visualization results

3. Results and Discussions

3.1 Mesh Sensitivity Analysis

Fig. 5 shows the mesh sensitivity analysis in graphical representation for the ease of interpretation. From the mesh sensitivity analysis, it is found that the optimum mesh size is 6mm since the maximum tensile stress is already achieving its convergence value and nearly constant with only small increments when smaller mesh size is applied. So, it can be concluded that smaller mesh sizes will provide more accurate results or outputs. However, other factors also need to be considered such as CPU time and wall clock time. Smaller mesh sizes require more computational effort to run the analysis completely. Long time taken required for an analysis to complete is not convenient especially when there are numbers of models to be analyzed.

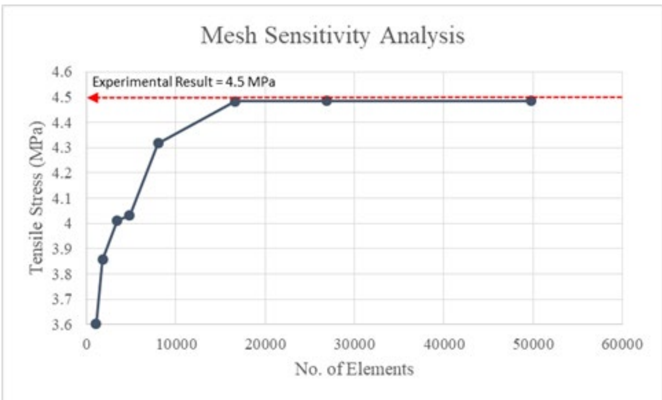

Fig. 5 - Mesh sensitivity analysis graph of stone SFRC splitting tensile model

3.2 Model Validation

Once the stress-strain relationship outputs were obtained, they were then compared with the experimental results and numerical analysis results by [5]. The splitting tensile strength from experimental results and numerical analysis results are tabulated in table 2. The tensile stress-strain results of brick concrete, brick SFRC, stone concrete and stone SFRC are shown in fig. 6.

From the numerical analysis results, the splitting tensile strength of brick concrete, brick SFRC, stone concrete and stone SFRC are found to 4.48MPa, 5.59MPa, 2.71MPa and 7.45MPa respectively if the results are taken from horizontal stress distribution. While if the results are calculated using the formula given by [13] from the compressive reaction force, the splitting tensile strength of brick concrete, brick SFRC, stone concrete and stone SFRC are found to be 4.21MPa, 5.06MPa, 2.73MPa and 6.63MPa respectively which are slightly lower than the results from horizontal stress except for stone concrete that is almost the same.

Table 2 - Splitting tensile strength from experimental results and numerical analysis results

	Experimental [5]	ANSYS [5]		ABAQUS using [13] equation		ABAQUS from Horizontal Stress	
	Tensile Strength (MPa)	Tensile Strength (MPa)	Difference (%)	Tensile Strength (MPa)	Difference (%)	Tensile Strength (MPa)	Difference (%)
Brick Concrete	4.5	3.67	18.4	4.21	6.4	4.48	0.4
Brick Steel Fibre Reinforced Concrete	6.5	5.00	23.1	5.06	22.1	5.59	14.0
Stone Concrete	3.0	2.79	7.0	2.73	9.0	2.71	9.6
Stone Steel Fibre Reinforced Concrete	7.6	5.04	33.7	6.63	12.8	7.45	2.0

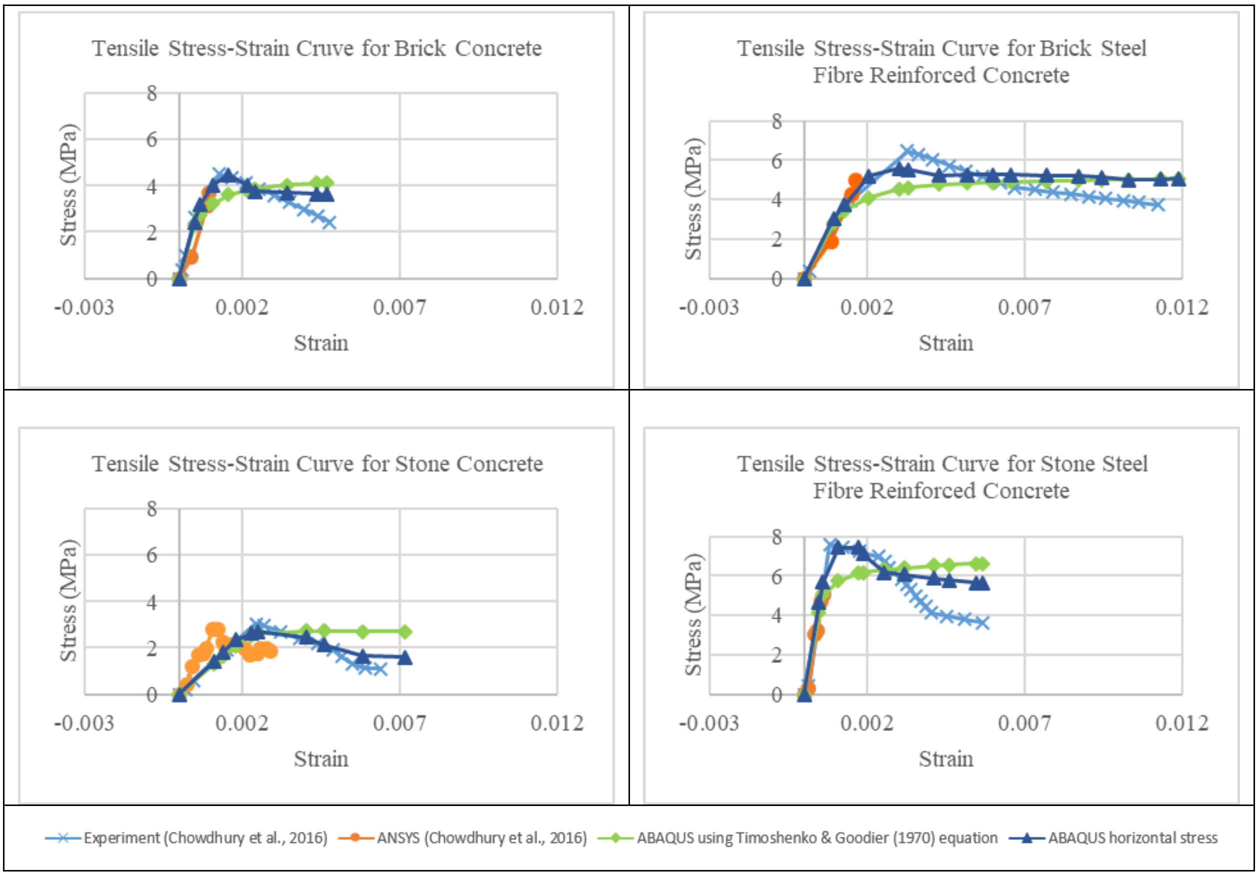

Fig. 6 - Tensile stress-strain relationship for (a) brick concrete; (b) brick SFRC; (c) stone concrete; and (d) stone SFRC

In addition, the numerical analysis results horizontal stress also shows better stress-strain relationship simulation of the experimental results when compared to results obtained by using the splitting tensile strength formula. The percentage difference between numerical analysis results from ABAQUS and the experimental results is less than 23% if the formula by [13] is used. While if results from horizontal stress is used, the percentage difference is less than 15%.

The incorporation of the splitting tensile strength equation by [13] for these models is observed to be producing results that are slightly lower than the experimental results. One of the possible contributing factors is, according to [12], the method for determining split tensile strength does not account for the sample size effect and compressive strength of concrete, which can have a dominant impact on the test results. This might also be the cause of underestimation of splitting tensile strength for the numerical analysis conducted by [5].

Furthermore, the discrepancies in the results also might be due to the compressive properties applied to the model because the strength is dependent on the compressive reaction force value as used in the formulation. The compressive stress-strain relationship obtained from experimental results as in Figure 2 is not having a full compressive response in order to give results to its full extent. Figure 7 shows the typical stress-strain for concrete behaviours according to [4] that is more extensive if to be used for numerical modelling. This also could be the reason why the numerical results by [5] happens to be up to the maximum stress only that are mostly linear except for the stone concrete results. However, the results are still satisfactory in order to estimate the working tensile stress of the concrete and steel fibre reinforced concrete.

Therefore, it can be concluded that the splitting tensile test simulation from this study by using ABAQUS platform are found capable of estimating the splitting tensile behaviour of plain concrete and SFRC made of brick and stone aggregates even though the post-peak failure behaviour of the models are not that precise.

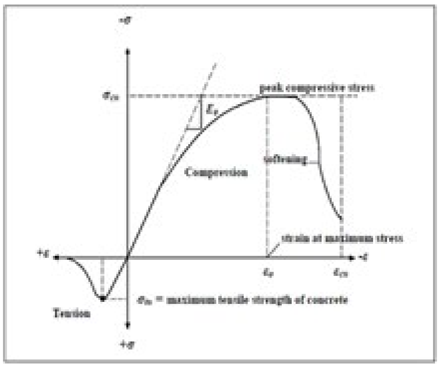

Fig. 7 - Typical stress-strain curve for concrete [4]

3.3 Simulation Governing Parameters

It is found that the main governing parameters to this numerical analysis were the elastic modulus and Poisson's ratio. It is usually assumed in reinforced concrete structural analysis and design that the material is isotropic and homogeneous globally. Fig. 8 shows the tensile stress-strain result from ABAQUS if elastic modulus from experimental compressive behaviour is taken as the Young's modulus for the model while fig. 9 shows the results if elastic modulus is adopted from experimental tensile behaviour.

a) Discussion on Elastic Modulus Parameter

From fig. 8 and fig. 9, it is observed that when tensile elastic modulus is adopted into the model instead of compressive elastic modulus, the stress-strain shape is closer to the experimental results especially in terms of the initial stress-strain slope relationship. The compressive elastic modulus is higher than the tensile elastic modulus thus producing steeper initial stress-strain relationship and slightly higher tensile strength to the numerical analysis results when compared to the experimental results. Since, the stress-strain results from using tensile elastic modulus is more accurate, thus it is taken as the Young's modulus of the concrete and SFRC concrete.

The elastic modulus of the concrete in compression and tension from the experimental results by [5] are very much different therefore making the concrete model to possess anisotropic behaviour and could also lead to instability of the model since the model in this study is created as isotropic model. This is also supported by [9] that when the elasticity modulus of concrete and fibre-reinforced concrete in compression and tension vary from each other, the widely used equality assumption of both values may have a negative effect on structural behaviour analysis and experimental evaluation. So, it cannot be assumed that the modulus of elasticity of the concrete in compression and in tension is the same to be used in the numerical analysis.

b) Discussion on Poisson's Ratio Parameter

Since the static Poisson's ratio usually ranges between 0.15-0.25 for hardened concrete according to [2], therefore this numerical trial applied the value within the range. As shown in fig. 10, different values of Poisson's ratio applied influence the shape of the tensile stress-strain especially for the post-peak stress behaviour.

From the results, it can be observed that different values of Poisson's ratio applied only give slight difference towards the initial stress-strain of the numerical results up to the peak stress, but then is observed to effect the shape of the post-peak stress behaviour. Besides, the peak stress value or the splitting tensile strength also varies for different Poisson's ratio applied. Hence, from the numerical trials, the Poisson's ratio that gives the closest shape of stress-strain relationship is taken as the concrete Poisson's ratio. The decent values of Poisson's ratio to all four models are tabulated in table 3.

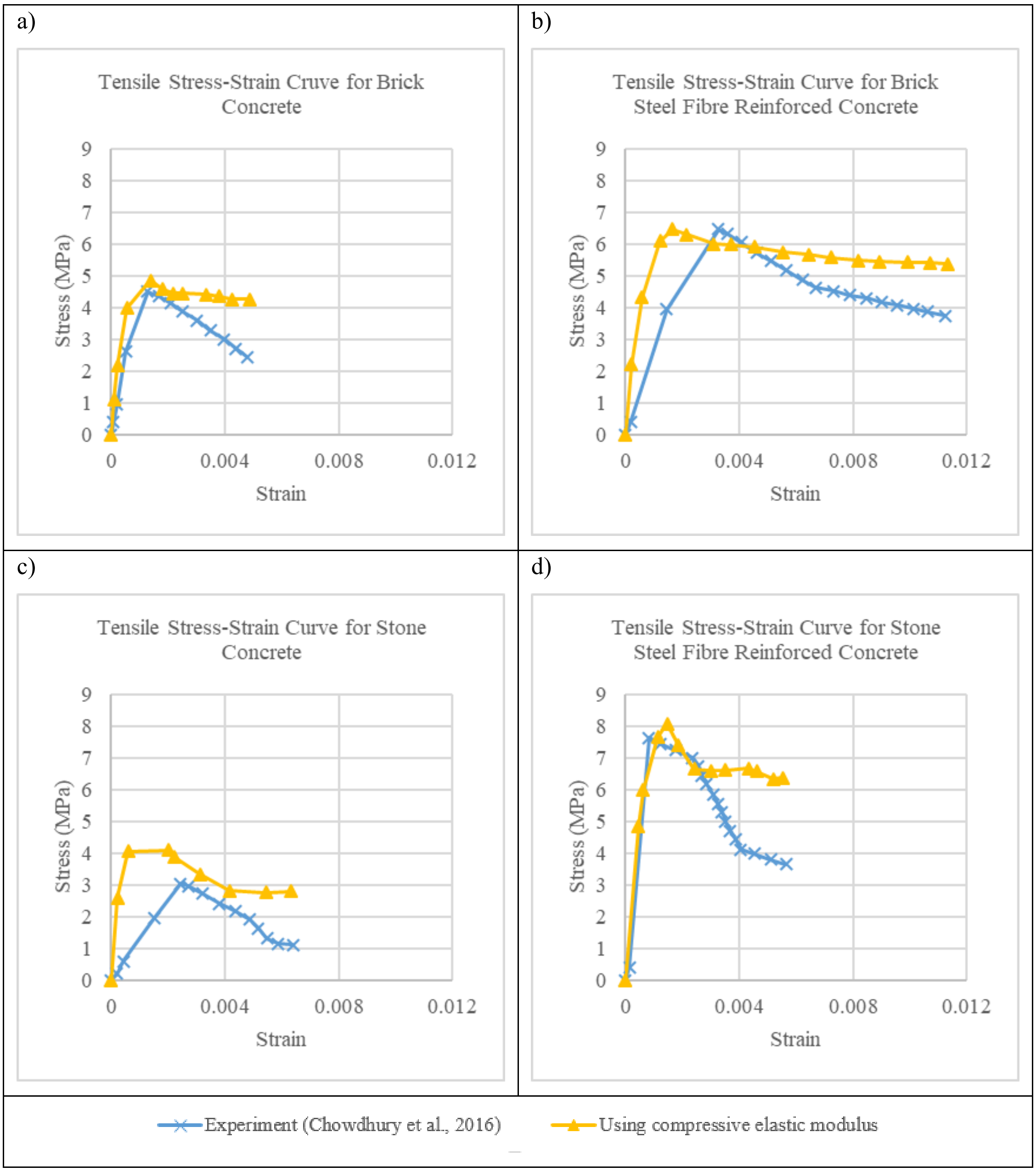

Fig. 8 - Tensile stress-strain using compressive elastic modulus

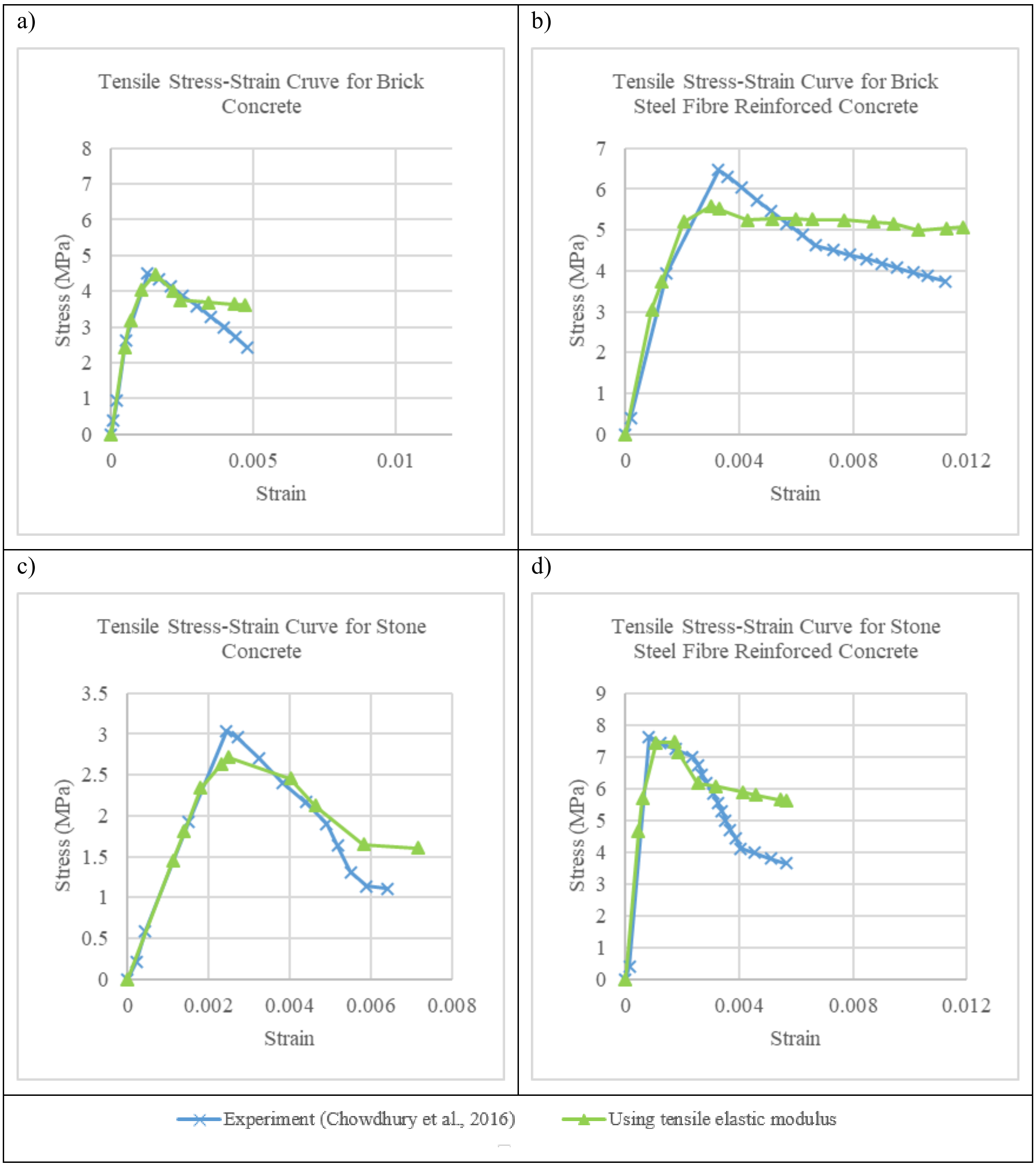

Fig. 9 - Tensile stress-strain using tensile elastic modulus

Table 3 - Poisson's ratio for concrete and steel fibre reinforced concrete models

Model	Poisson's ratio
Brick Concrete	0.20
Brick SFRC	0.25
Stone Concrete	0.25
Stone SFRC	0.25

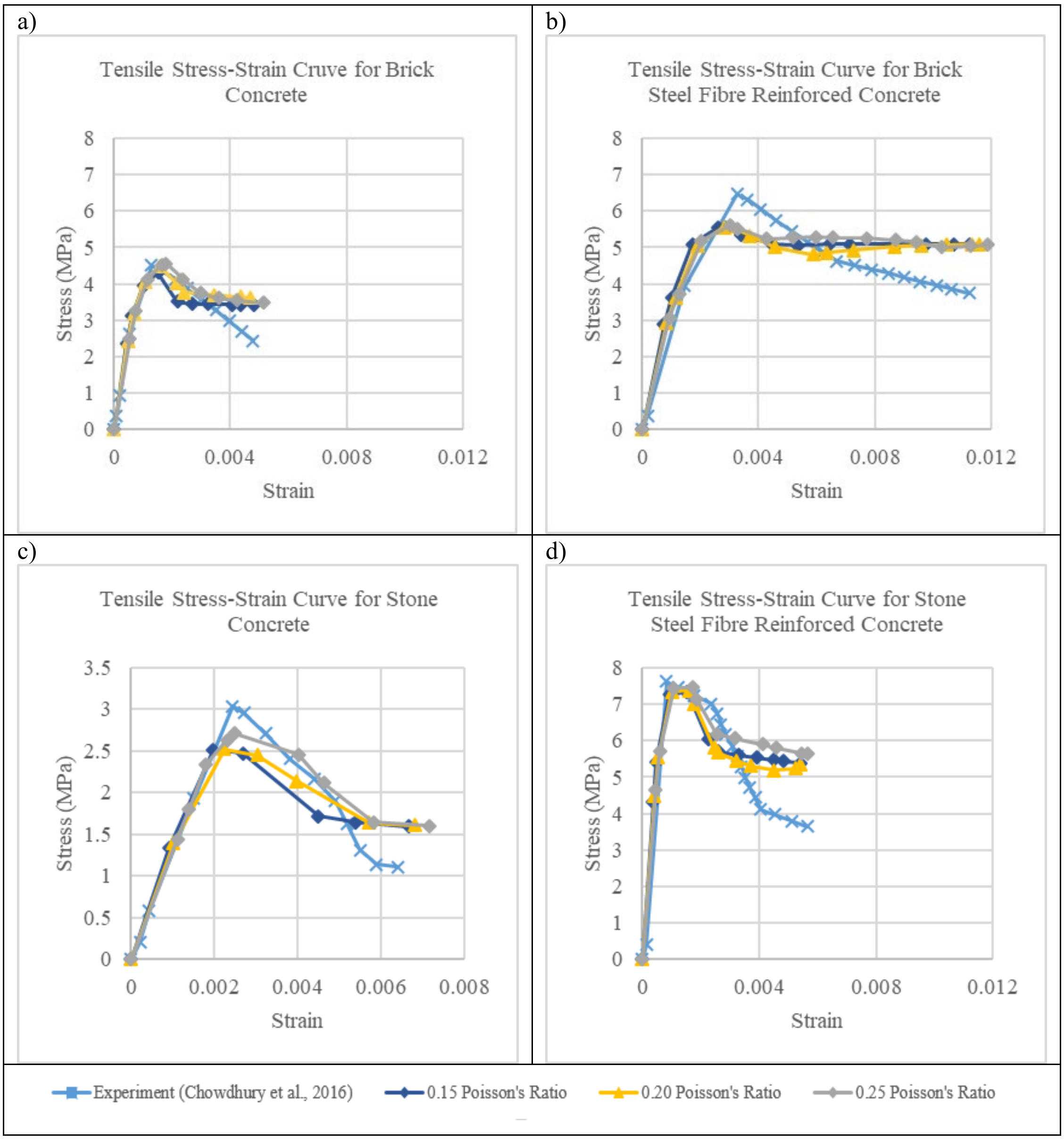

Fig. 10 - Tensile stress-strain with different Poisson's ratio

3.4 Evaluation of Stress Contour

Fig. 11 shows the horizontal stress contour of brick concrete, brick SFRC, stone concrete and stone SFRC models which indicates the tensile stress distribution. From the results of horizontal stress contours shown in fig. 11, the tensile stress concentration is observed to be in the direction of line loading, which also approves with cracks developed in the same direction experimentally. The contours of the horizontal stresses, see fig. 11.a), are almost uniformly distributed, in particular in the diametral direction of the disk. In plain concrete and SFRC, the stress contours are found to be quite similar, but the SFRC displayed greater load carrying ability prior to failure compared to plain concrete. Furthermore, since the horizontal stress concentrate along the direction of the loading, it also conforms to the measurement of splitting tensile strength at the middle of the cylindrical concrete section as illustrated by [7] in fig. 4. Therefore, the selection of elements at the centre of the concrete section as splitting tensile stress measurement in the numerical analysis is reasonable. As concluding remarks, the results show that the horizontal stress distribution for all the splitting tensile specimen models are quite the same except for the magnitude due to different stress capacity or strength.

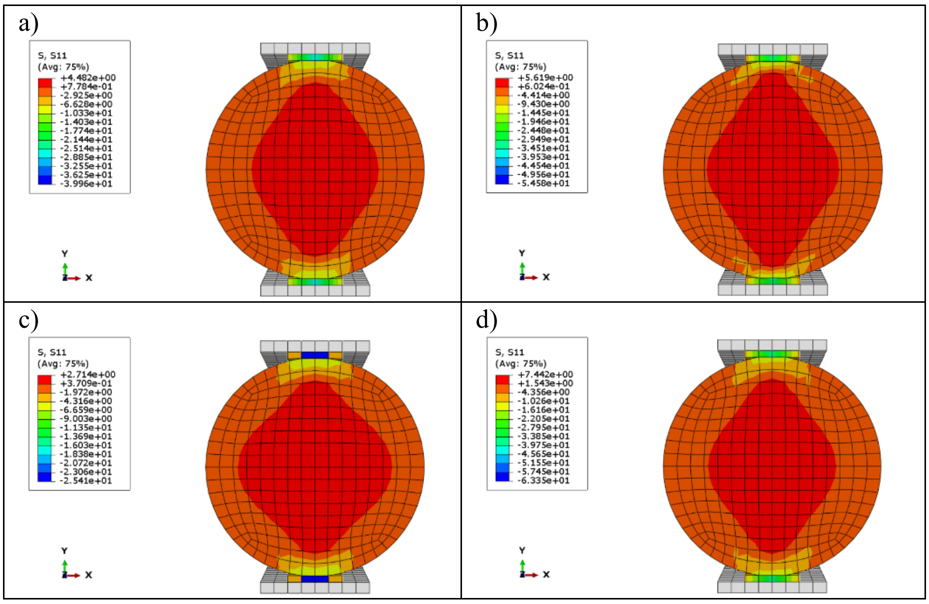

Fig. 11 - Horizontal stress contour of (a) brick concrete; (b) brick SFRC; (c) stone concrete; and (d) stone SFRC

3.5 Evaluation of Failure Patterns and Tensile Damage

Fig. 12 shows the tensile failure patterns of brick concrete, brick SFRC, stone concrete and stone SFRC. These failure patterns of specimens from experimental testing are then compared with the tensile damage from finite element modelling. From the splitting tensile test of the brick concrete and stone concrete, it is observed that the control specimens splitted into half as a result of tensile failure. This indicated that the control specimens are brittle. Then when after about 1.5% volume fraction of steel fibres were added to the concrete mix, other than improvement of tensile strength, the failure pattern also has changed from brittle to ductile and the specimens did not split into half. In order to produce concrete that is more durable with improved ductility, steel fibres are found to be very effective. This is because they serve as crack arrestors and avoid the propagation of cracks by bridging when steel fibres are applied to a concrete mix. Furthermore, the steel fibres also act as stress transfer media since they are properly bonded with the concrete mix thus avoiding sudden failure which could be more life-saving if a structure is reaching its ultimate limit state and undergoing structural failure. In fact, the residual capacity of steel fibre reinforced concrete (SFRC) can be considered as one of the main advantages of implementing SFRC in the structural applications that are expected to suffer impact damage. This will surely be very helpful when there are needs to perform evacuation and recovery operations as well as structural rehabilitation.

The failure patterns or tensile damage produced from this simulation attempts are not really as realistic as the experimental testing but it still can depict the horizontal tensile damage that is usually seen in splitting tensile test. The second column of fig. 12 shows the early tensile damage of splitting tensile model at peak stress for the brick concrete, brick SFRC, stone concrete and stone SFRC respectively. It can be seen that the damage occurs at the centre of the cylindrical concrete specimen because the tensile stress concentrate along the direction of the applied load. Then the damage propagates upward and downward and the concrete start losing its tensile stress capacity due to degradation once the tensile strength of the material is reached. The third column of fig. 12 shows the post-peak stress tensile damage in which the damage zone has grown bigger that indicates the propagation of the tensile damage. All tensile damage happens to be showing quite similar pattern or zone of failure and its propagation for all models except for the brick SFRC. The tensile damage on the brick SFRC is a little bit different compared to other three models because of its ductility. As shown in fig. 6 for the stress-strain relationship result of brick SFRC, the strain almost reaches a value of 0.012 which is very high compared to other specimens. Therefore, the numerical analysis tensile damage result for brick SFRC might indicate its ductile behaviour.

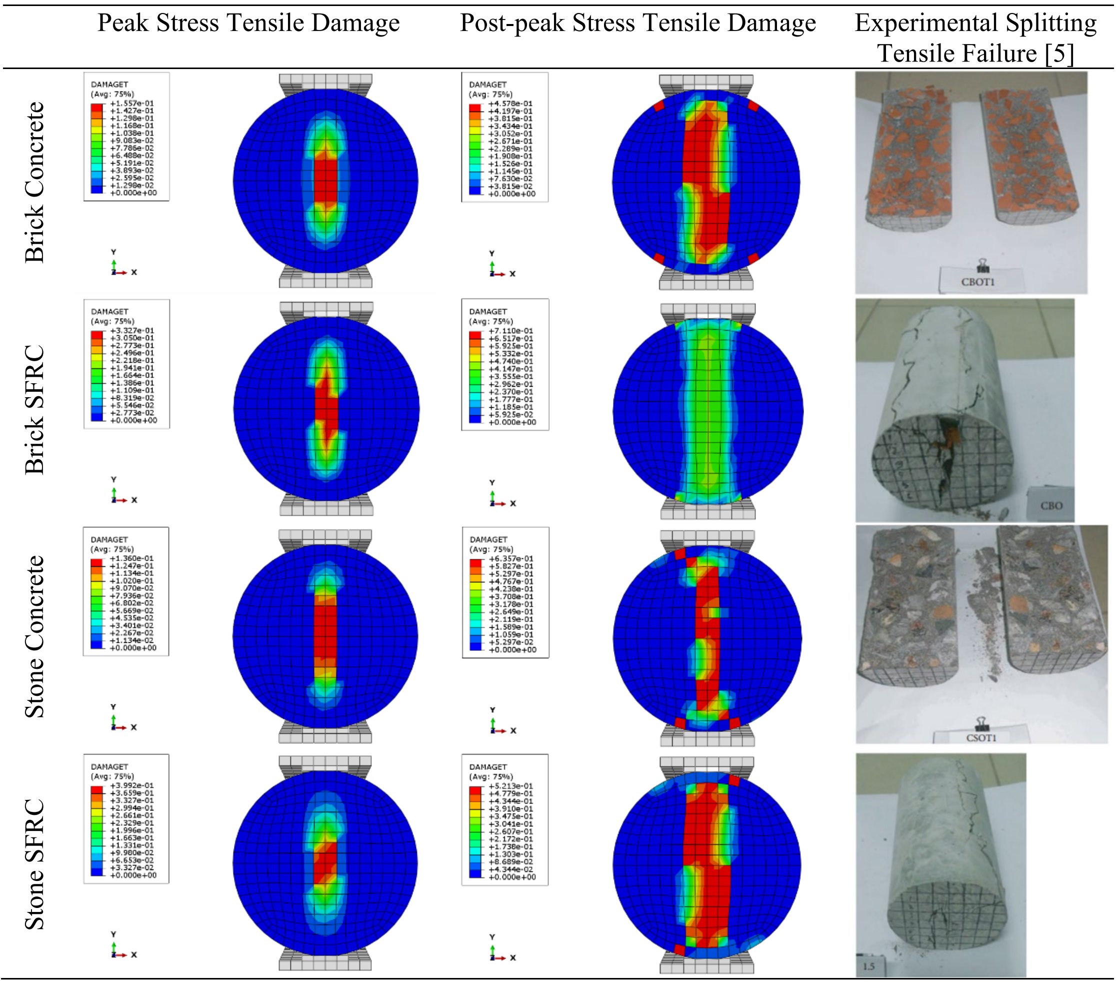

Fig. 12 - Tensile failure or tensile damage of concrete specimens and models

4. Conclusions

It is found that this model is suitable in studying non-linear tensile behaviour of concrete and steel fibre reinforced concrete especially when stress-strain relationship and concrete damage are the main focusses of the study. The tensile stress-strain relationship for all four models are found to have good correlation with the experimental results up to peak stress and partly on the post-peak stress behaviour. The tensile damage results from this numerical analysis also are found to be satisfactory and acceptable when compared to the experimental results.

Furthermore, the splitting tensile strength of concrete and steel fibre reinforced concrete can be predicted from the numerical analysis conducted in this study. The tensile strengths are obtained from two methods which are from horizontal stress results and from the formula based on the work by [13]. The results from horizontal stress are closer to the experimental results while results from the formulation are slightly lower. The possible contributing factor is that the method for determining split tensile strength does not account for the sample size effect and compressive strength of concrete, which can have a dominant impact on the test results. However, it is better to slightly underestimate the splitting tensile strength for safety precautions rather than overestimating the strength especially when it comes to estimating the ultimate strength.

Next, the numerical analysis of the splitting tensile strength test is found to be governed by these two important parameters which are elastic modulus of concrete and Poisson's ratio. For this study, the elastic modulus that should be taken as the Young's modulus in the model is the tensile elastic modulus instead of compressive elastic modulus. Tensile stress-strain results from using tensile elastic modulus as the model Young's modulus is very much closer to the experimental results compared to when compressive elastic modulus is used. The equality assumption of both values cannot be used in this numerical analysis. As for the Poisson's ratio, since the Poisson's ratio value for hardened concrete usually ranges from 0.15-0.25, numerical trials are done within the range. The Poisson's ratio value that gives the closest tensile stress-strain results to the experimental results is taken as the concrete Poisson's ratio. All in all, the adopted 3D model using ABAQUS platform captured reasonably well the reaction of the concrete cylinders subjected to splitting tensile test. The numerical analysis done for this study are able to estimate the splitting tensile strength and behaviour of plain concrete and steel fibre reinforced concrete.

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