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Finite element analysis of the flexural behaviour of steel-reinforced GEM-TECH cementitious material

Ucheowaji Ogbologugo, Messaoud Saidani, Adegoke Omotayo Olubanwo* and Eoin Coakley

School of Energy, Construction & Environment, Coventry University, Coventry, West Midlands, UK

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This paper presents a numerical investigation on the flexural performance of a novel cementitious reinforced GEM-TECH material using finite element method. A discrete nonlinear FE model using the commercial software ANSYS was employed to model a steel-reinforced GEM-TECH beam. Element SOLID65 was used to model the cementitious material while LINK180 element was used to model the reinforcing bars and stirrups. For model validation, FEA results and crack plots were compared to those obtained from the experimental results of five reinforced GEM-TECH beams: three beams designed with target density of 1810 kg/m^3 and two beams with target density of 1600 kg/m^3. Both load-deflection plots and the failure mode crack plots predicted by the FE model were in good agreement with the experimental results.

1. Introduction

The application of lightweight cementitious structural materials in high-rise buildings such as residential and other complexes would reduce the dead weight of these buildings on their foundation (Kosmatka et al., 2002). It would also reduce the effect of seismic and wind loads in earthquake prone areas (Lee et al., 2014); as the effect of the force is a function of the mass of the structure and the acceleration due to gravity, which is constant. Other important benefits from the use of lightweight cementitious materials like foamed concretes are their low thermal conductivity and the elimination of the energy required for aggregate extraction and transport. However, the use of lightweight cementitious materials for structural purposes has been limited due to the poor engineering properties of the material resulting from low compressive strength values; and where lightweight aggregates have been used to improve such properties, the issue of mass manufacturing and availability of such lightweight aggregates arises. Further research on developing lightweight materials that would be efficient in terms of cost and reduced carbon emission (resulting from cement consumption) inspired the development of the GEM-TECH material.

The GEM-TECH material is a cementitious lightweight material developed by Gem-Tech Technology and has been proposed for structural applications. The material is made up of basic raw materials: sand, cement, water and an aqueous solution of the GEM-SOL catalyst (see Table 1). The GEM-SOL catalyst is an organic surfactant made of 3% Ferrous sulphate and 92% organic waste

* Corresponding author. Tel.: +44 (024) 77658711
E-mail addresses: aa7878@coventry.ac.uk (A.O. Olubanwo)

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materials such as sludge, etc. Other components by volume includes: 2.5% Sodium Hydroxide and 2.5% Hydrochloric acid. The principles of air entraining were adopted for the production the GEM-TECH material, which gives it some similar physical characteristics to foamed concrete. The lightweight material requires less cement consumption for production and therefore has the potential of contributing to lower CO_2 emission when used as a structural member for low/medium strength structural applications instead of normal weight concretes. Maiden tests on the engineering properties of the GEM-TECH material shows comparable strength values to that of normal weight concrete of grade C20/25 and C25/30 even though they are about 23% to 30% lighter (Dan-Jumbo, 2015; Ogbologugo, 2016). According to Kosmatka et al. (2002) a lightweight cementitious material is considered as a structural material if it attains a 28-day compressive strength above 17 MPa for density ranges between 1350 to 1850 kg/m^3. Since the GEM-TECH material can be classified as a structural material, it is therefore, important to fully study and understand the behaviour of the material when subjected to structural loading.

Table 1. Composition of GEM-TECH Material

Material Target Density (kg/m^3)	Cement (kg)	Sand (kg)	Water (kg)	GEM-SOL (kg)	Solution water (kg)
1810	261.0	1247.8	227.4	2.35	8.90
1600	225.85	1080.64	186.22	2.70	13.57

Flexural loading is a generic form of loading experienced by structural members. Therefore, for any structural material, an understanding of their behaviour under flexural loading will highly influence its applicability. Such traits as the failure loads, failure pattern, crack formation and propagation for individual materials need to be understood for effective and efficient use of the material in construction. Jones and McCarthy (2005) tested some reinforced foamed concrete beams subjected to flexural loading and concluded that they show similar failure mode and behaviour to that of conventional concrete of 25 MPa strength class. However, their study pointed out that foamed concretes would deflect up to 2.3 times that of conventional concrete beam of normal weight.

The comprehensiveness of the finite element method in producing solutions to various physical and structural phenomena in many fields of science makes it a useful tool in modelling the behaviour of materials (Ševelová and Florian, 2013). The advent of computer programmes and software like ANSYS, ABAQUS, etc., that solves complex mathematical equations and adopts a user-friendly interface for modelling and simulations, has made analysis become less rigorous and less burdensome. Several finite element models have been developed to study the behaviour of normal weight reinforced concrete beams in flexure (Badiger & Malipatil, 2014; Buyukkaragoz et al., 2013; Jnaid & Aboutaha, 2015; Ibrahim and Mahmood, 2009) and shear (Potisuk et al., 2011; Qapo et al., 2016). Most of the studies have focused on modelling normal weight concretes. However, Goh et al. (2014) developed a finite element model to study the foamed concrete cube that is subjected to compression and Al-Rousan (2016) also studied shear failure on lightweight aggregate beams using finite element methods. The GEM-TECH material is a novel product and no finite element models have been developed so far to study its behaviour and to predict its failure mode/ pattern.

This paper seeks to characterise and study the behaviour of a reinforced beam made from GEM-TECH material by developing a finite element model using ANSYS 16.1. A successful characterisation of the material using ANSYS will produce a validated model from which a large range of parameters can be easily eliminated; such investigation that may be difficult and burdensome to set up in the laboratory. Also, an understanding of the failure pattern of the material will boost knowledge of its application for the most efficient use of the material.

2. Finite Element Modelling

The finite element modelling for the reinforced GEM-TECH beam was carried out using ANSYS 16.1. The size of the beam is 80 × 180 × 1500 mm subjected to four-point loading as shown in Fig. 1. Two grades of the GEM-TECH beam were analysed- the D1600 and D1810 beam which represents GEM-TECH materials designed to have a dry density of 1600 kg/m^3 and 1810 kg/m^3 respectively. The beams are reinforced with two 10 mm diameter bars and 8 mm diameter stirrups spaced at 80mm within the shear span of the beam.

2.1 Defining element types for the reinforced GEM-TECH beam

The GEM-TECH cementitious material is modelled using the SOLID65 element, which is modelled as a 3-dimensional element with 8 nodes, each having 3 degrees of freedom. This element has cracking and crushing capabilities; it also has provision for inputting material data such as shear transfer coefficients, compressive and tensile stresses, handles non-linear behaviours, etc. (ANSYS, 2013). Enhanced convergence of solution was implemented in the analysis to accommodate cases where elements are completely crushed. This action transfers stresses from crushed elements to uncrushed elements and sets the mass of the crushed elements to zero. Solution control feature was adjusted to account for stress relaxation on cracked elements.

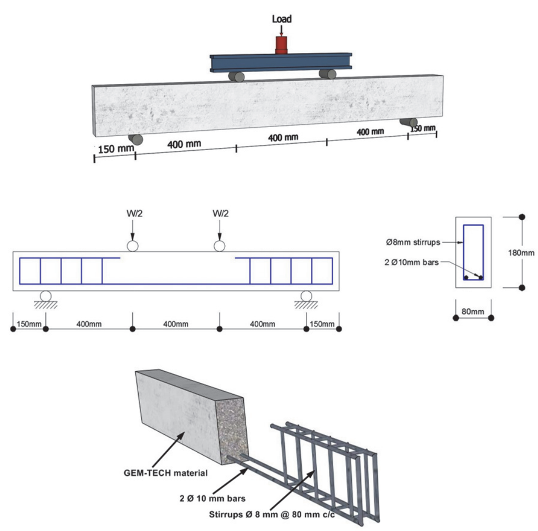

Fig. 1. Four-point loading arrangement of beam and reinforcement layout

The discrete model approach was adopted, therefore, LINK180 element was used to model the reinforcement bars and stirrups; the element is uniaxial with tension-compression capabilities, and can translate in nodal x, y and z directions, having 3 degrees of freedom on each node. Fig. 2. gives an illustration of the elements' geometry and nodal positions.

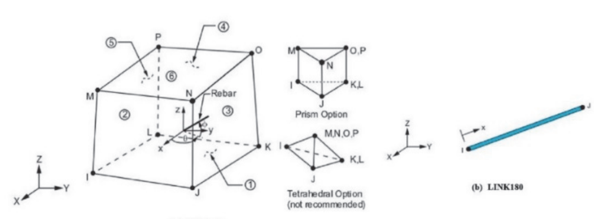

Fig. 2. Element types for FE model of reinforced GEM-TECH beam on (ANSYS, 2013).

The real constants defined for the elements used in the FE modelling of the reinforced GEM-TECH beam is as shown in Table 2.

Table 2. Real Constant for the elements used in the FE model

Real Constant Set	Element Type	Constants			
1 GEM-TECH (D1810/ D1600)	SOLID65		Rebar 1	Rebar 2	Rebar 3
		Material number	0	0	0
		Volume ratio	0	0	0
		Orientation angle θ	0	0	0
		Orientation angle β	0	0	0
2 Steel Reinforcement	LINK180	Area of cross-section (mm^2)	78.5		
		Initial strain (mm/mm)	0		
3 Stirrups	LINK180	Area of cross-section (mm^2)	50.3		
		Initial strain (mm/mm)	0		

2.2 *Material model for FEA of the reinforced GEM-TECH beam*

The material model for a FE model on ANSYS is dependent on the nature and engineering properties of the material; for this paper, the engineering properties for the GEM-TECH material inputted in the model were based on laboratory testing while that of the steel reinforcement was established properties of steel from literature (Materials data book, 2003). The GEM-TECH material shares some similar characteristics as concrete; for example, it can be described as quasi-brittle too and under compression lower than a third of its compressive strength, it portrays a linear elastic trend. The linear elastic trend for the material is defined by inputting values of elastic modulus and Poisson's ratio as shown in Table . The non-linear behaviour of the GEM-TECH material is governed by inputting values for multilinear isotropic hardening obtained from the stress-stress relationship for the material from experiments. The bilinear isotropic hardening was defined for the steel bars and stirrups by inputting values for the yield stress and tangential modulus of 410 MPa and 20 MPa, respectively.

Table 3. Linear elastic property of reinforced GEM-TECH beam

Linear Isotropic Material Properties			
	D1810	D1600	Reinforcement bar
Elastic Modulus (GPa)	11.17	16.41	210
Poisson's ratio	0.20	0.20	0.3

Non-metal plasticity models were also defined for the GEM-TECH material by assigning values between 0 and 1 to the shear transfer coefficient (open and closed) for the materials. The shear transfer coefficient is responsible for modifying the stress-strain relationship of the material during crack formation or crushing, thus reducing the resistance to stress in the direction normal to the plane of crack. The non-metal plasticity for both sets of the GEM-TECH material is as shown in Table .

Table 4. Non-metal plasticity for GEM-TECH material

	D1810	**D1600**
Open shear transfer coefficient	0.4	0.4
Closed shear transfer coefficient	1	1
Uniaxial cracking stress (MPa)	3.13	3.70
Uniaxial crushing stress (MPa)	20.05	25.67

2.3 Geometric modelling and meshing

The behaviour of two sets of reinforced GEM-TECH beams under four-point loading were studied experimentally and used for validating the model for this study. The experimental set up is shown in Fig. 1. The two sets of beams were based on different design densities; the D1810 denoting the GEM-TECH material designed to attain a target density of 1810 kg/m^3 and D1600 denoting the GEM-TECH material designed with a target density of 1600 kg/m^3. Three sets D1810 and two sets of D1600 beams were studied in the laboratory and used for validation of this study. Half of the beam from the experimental setup was modelled on ANSYS, and symmetry boundary condition was defined at the centre face of the beam. This was done to reduce the analysis domain so that finer mesh can be used to create smaller elements for a more accurate result. The beam was modelled as a volume while the reinforcement bars and stirrups were modelled as line elements along the nodes of the beam element. A fine mesh size was adopted with average edge length for individual elements of 10 mm were adopted. Slip of rebar was precluded in the model.

2.4 Loading, boundary conditions and analysis settings

Displacement control loading was adopted for this model to enhance convergence and according to Rust et al. (2006), this would stabilise the analysis in a way that enhances convergence so that the failure load can be reached. The sets of nodes corresponding to the positions of the rollers at the load application point and support points respectively were coupled using the 'couple DOF' command. The lead node for the coupled set representing the support was assigned a displacement value UY = UZ = 0, whereas the lead node for the coupled set representing the loading point was assigned a displacement value in the negative Y direction.

3. Results and Discussions

3.1 Load-deflection behaviour of the GEM-TECH material

The load-deflection plot from the FEA of the D1810 and D1600 beams were plotted against results from sets of beams tested experimentally as shown in Fig. 3.

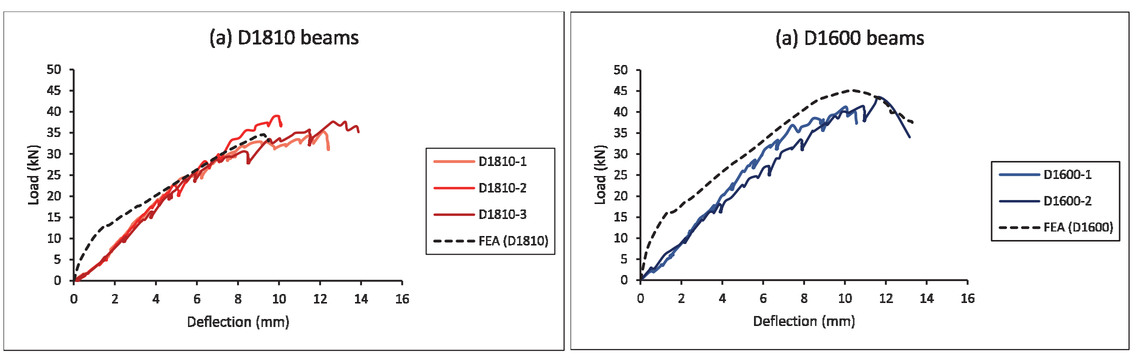

Fig. 3. Comparing the load deflection plot from FEA with experiments.

The load deflection plot from Fig. 3 shows that there is a similar trend between the FE plot and that obtained from experiments. The FEA plot shows a steeper slope at initial loading stages followed by a kink in the shape resulting from crack formation at the beam soffit making the beam member to experience loss of stiffness after which the slope of the plot then gradually becomes less steep until it flattens up as it approaches the failure load during which cracks propagate and spread within the beam and some elements also experience crushing. The load at which the first crack was recorded in the FEA was 15 kN and 14.8 kN for the D1600 and D1810 respectively whereas the load at which the first visible crack was observed from experiments on the average was 14 kN for both the D1600 and D1810 beams. Fig. 3 also shows that the failure load for the various beams tested experimentally fall between 12% range from the failure load from FEA prediction. The failure load from FEA is observed to be about 12% greater than theoretical prediction. The theoretical predictions were based on analysis of stress block from the loading arrangement in Fig. 1 by equating the maximum moment from the arrangement with the moment of resistance from the stress block. The moment of resistance was calculated using the Eq. (1) (Megson, 2014):

$$M_r = 0.156 f_c b d^2 = 0.65 f_y A_s d, \tag{1}$$

where M_r is the moment of resistance, f_c is the compressive strength of the material, b is the width of the beam, f_y is the yield strength of steel, A_s is the cross sectional area of steel and d is the effective depth of the beam. The maximum moment from the load arrangement is given by:

$$M_{max} = Wa/2, \tag{2}$$

where W is the load applied to the beam while 'a' is the distance between the roller support and the load points (shear arm) and is equal to 400 mm from the loading arrangement as shown in Fig. 1.

Equating Eq. (1) and Eq. (2) we have the theoretical failure load as:

$$W_{max} = 0.312\, bd^2 f_c / a. \tag{3}$$

Table 5. Comparing FEA values of failure load to both experimental and theoretical values

Specimen	Failure load (kN)		
	Theoretical prediction	FEA	Experiment
Beam D1810-1	33.3	34.6	35.2
Beam D1810-2			38.9
Beam D1810-3			37.6
Beam D1600-1	40.0	45.1	41.2
Beam D1600-2			43.6

At initial loading stages, the curve for experimental plot for the beams were less steep compared to the FEA plot and this can be attributed to the perfect conditions assumed by the FEA such that there is perfect bonding between the material and steel reinforcing bar. Also, minor issues like the effect of bond slip occurring between the material and steel reinforcing bar was not within the scope of this paper and this may also be responsible for the slight difference in the steepness of slope at the initial loading stages and the slightly higher failure load of the FE model over the experimental results. According to Ibrahim and Mahmood (2001), micro-cracks within the cementitious resulting from drying shrinkage and handling also contributes to the difference in stiffness between experimental load-deflection curves and that of FEA. Machine stiffness can also contribute to the difference in steepness in both sets of curves. The use of the GEM-TECH material as a beam that supports flexural loading can be given a consideration based on the FEA results as seen in the load-deflection plot, however, subject to investigation on its response to other forms of loading other than flexure. It shows that the material is good in flexure even though a high value of deflection was also recorded for both sets of beams.

3.2 Load-Stress behaviour/ distribution

The stress distribution of both the D1810 and D1600 GEM-TECH beams along the depth at mid-span is plotted in Fig. 4. The stress plot in Fig. 4 shows that the compressive stress at the upper fibres of the beam at the centre continues to increase. However, at failure of the beam only 60% of their compressive strength capabilities have been exhausted.

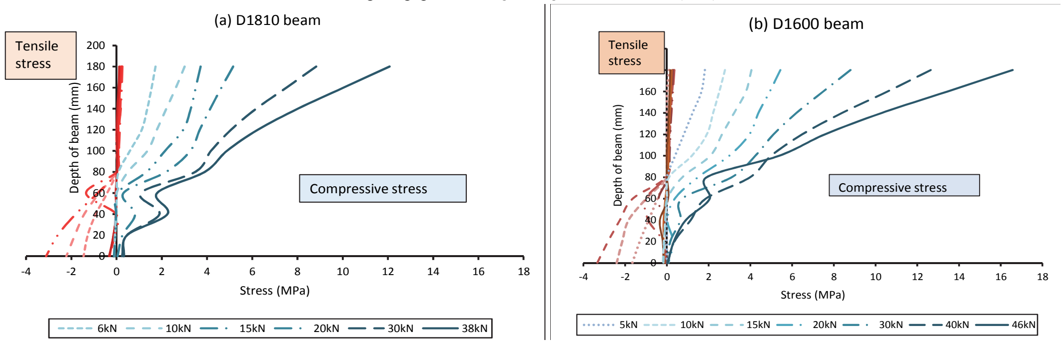

Fig. 4. FE plot for stress profile at the centre of the beam

This means that the GEM-TECH beam had not failed as a result of the crushing of the material at the compressive face of the beam at the centre, but a high stress concentration, up to the maximum compressive stress of the material, at the load application points and support roller positions has caused it to fail. This trend was similar for FEA results for both the D1810 and D1600 beams as shown in compressive stress contour plot in Fig. 5.

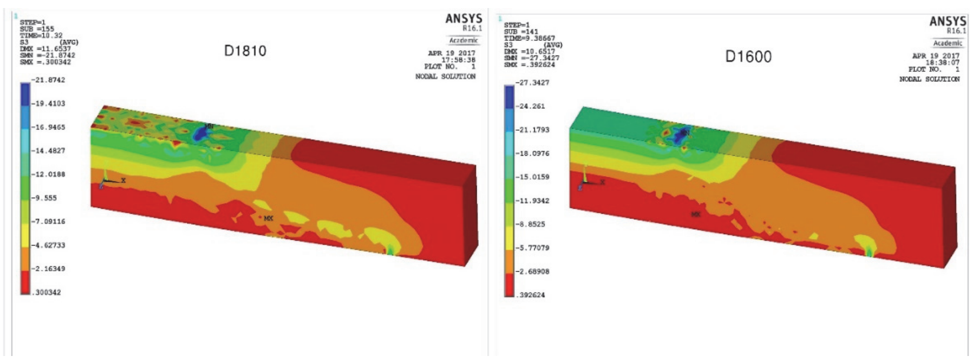

Fig. 5. Compressive stress contour plot from ANSYS for GEM-TECH beam

The GEM-TECH material mix does not contain coarse gravel and therefore, offers a lesser resistance to crushing and crack propagation that would have resulted from interlocking of these gravels. Results from the work of Wahyuni et al. (2012) showed that the interlock capabilities of coarse gravels in a cementitious mix is a major contributing factor to their shear capacity, resistance to crushing and crack propagation through it. Thus, the high concentration of stress resulting from the very small contact area between the roller and the material had caused local crushing of the material. The build-up of stress around the load application point and the supports, therefore, results in local crushing of the material. The GEM-TECH material, like most other foamed concretes, tends to fail in shear or due to high concentration of compressive stresses that causes the member to crush locally rather than flexure. This means that the application of GEM-TECH material as a structural material would be limited to areas that are not exposed to high concentration of stresses resulting from loads to cause local crushing; however, in areas where the loads are evenly distributed and not having high stress concentrations, the GEM-TECH material can be very effective in flexure.

Fig. 4 also gives a profile of the tensile stress across the depth of the beam at the centre face. The tensile stress at the soffit of the beam at the centre face continues to build until the maximum tensile strength is reached and then the elements experiences cracks and is no longer capable of resisting further tensile stresses. The load at which the maximum tensile stress is reached at the centre face of the beam as shown in stress profile plot (Fig. 4) is 15 kN. This corresponds to the load at which the first visible crack appeared from experimental observations. After the occurrence of cracking in an element, it is no longer able to resist stresses and therefore, the tensile stress at the soffit falls back to zero with further increase in the load. Most of the tensile stresses are carried by the reinforcing steel, however, when an element of the GEM-TECH material cracks, the tensile stresses are transferred to un-cracked elements of the GEM-TECH material via bond action with the reinforcing steel bars.

3.3 Stresses in reinforcing bars

The finite element ANSYS model for this work has assumed a perfect bonding between the GEM-TECH material and the steel reinforcement bars. The tensile stresses on the reinforcement are as shown in the contour plot in Fig. 6. The contour plot from ANSYS FEA shows that, at failure, the reinforcements embedded in the D1810 beam had not reached its maximum tensile strength value, whereas, for the D1600 beams, the area of the reinforcement at the centre of the beam had reached the maximum tensile stress. The observation was expected for the study because the beams were over reinforced so that the GEM-TECH material fails first so that failure of the material can be studied. The GEM-TECH material for D1810 failed even before the reinforcement is fully stressed (the longitudinal bars were stressed to 97% of the tensile strength) and the GEM-TECH material for the D1600 beam failed just when the reinforcements were beginning to yield.

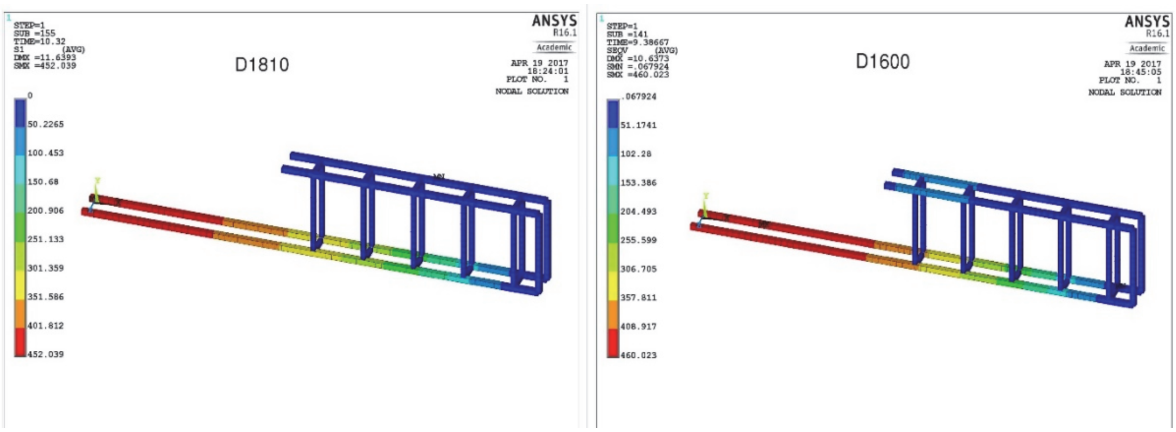

Fig. 6. Tensile stresses in reinforcing bars

Results from experiments show that the D1600 GEM-TECH material offers better resistance to compressive and flexural loading than the D1810 GEM-TECH material; thus, for similar reinforcements provided for both sets of samples, FEA results show that the D1600 beam displayed a more balanced section than the D1810 beam because the former had the GEM-TECH material and steel reinforcement bars reaching their maximum limits for compressive and tensile stress capacities respectively at the same time.

3.4 Load-strain behaviour

The strain profile across the depth at the centre face of the beam is given in Fig. 7. The graph shows that with increase in the flexural load on the beam, both the tensile and compressive strains at the bottom and top regions of the beam respectively increases. At initial loading stages, the strain distribution tends to be linear across the depth of the beam at the centre face cutting through the neutral of the beam. The tensile strain at the soffit of the centre face of the beam increases as the load increases but there is a significant jump in the strain value after the crack load of 15 kN was reached and this is similar for both sets of beams modelled. This jump in the strain values is an indication of the occurrence of crack and therefore there is an increased rate of development of tensile strain when the load continues to increase. When the load is increased further, the nonlinearity of the strain plot becomes more obvious, however, despite the jump in the tensile stress at the soffit of the beam at the centre face, the depth of neutral axis (the vertical intercept of the curve) tends to increase; this is because the section is slightly over reinforced and the section of GEM-TECH material above the reinforcing steel experiences increasing compressive stresses as the reinforcing bars had barely yielded before the failure of the beam.

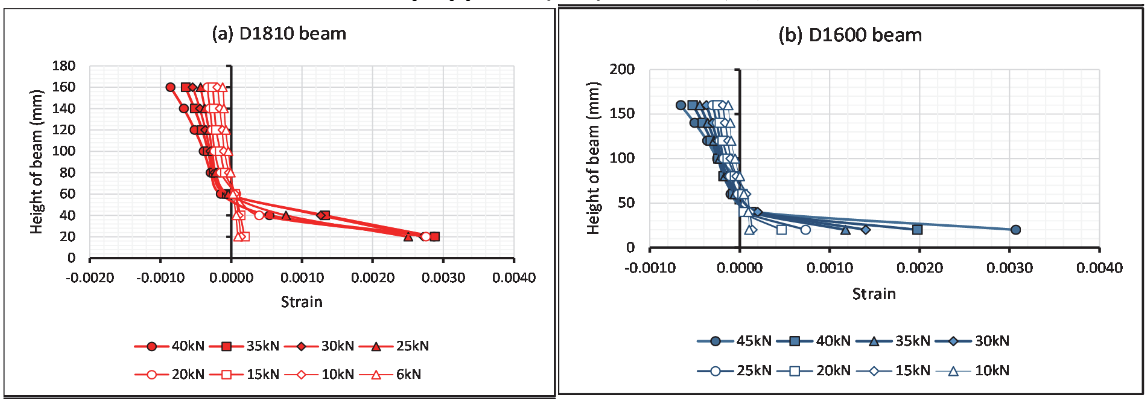

Fig. 7. Profile of Strain distributed across the depth of the beam at the centre face from FEA

The tensile strain distribution throughout the beams from FEA is given in a contour plot as shown in Fig. 8.

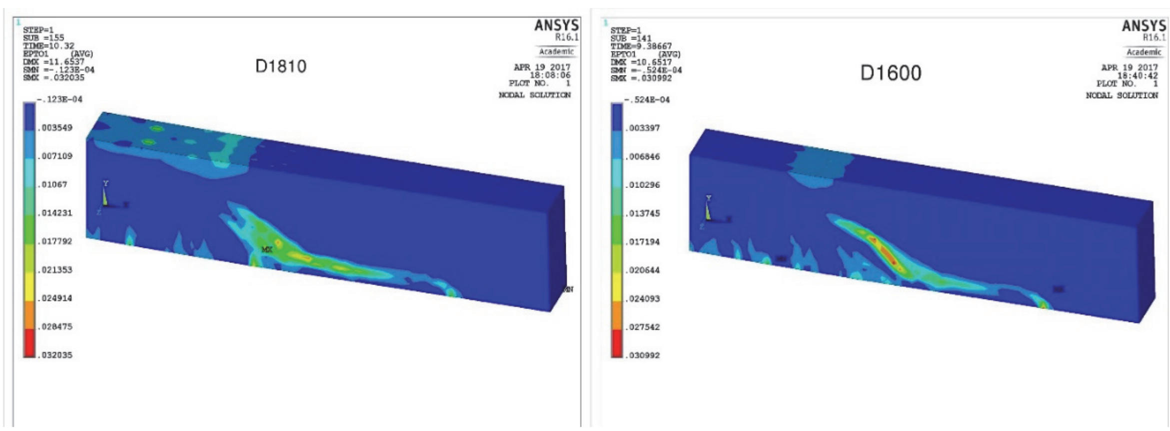

Fig. 8. Tensile strain in the GEM-TECH material

Fig. 8 shows that the maximum strain occurring in the beam resulting from shearing rather than flexure. When the strain occurring in the material at any point in the material exceeds its strain capacity, cracks develop at that point. Thus, tensile strain plot also gives an indication of the possible areas in the beam where crack would develop in the material that will lead to eventual failure of the beam. The contour plot indicates that the strain in the GEM-TECH member is maximum within the shear arm of the beam (at the possible location of shear cracks) for the D1810 beam and at the support point where local crushing of member resulting from softening at that point for the D1600 beams. The strain plot gives an indication that the GEM-TECH material is more susceptible to shear failure than flexure because the material offers less resistance to shear and crack propagation when compared to normal weight concrete.

3.5 FEA prediction of the failure mode and cracking behaviour of reinforced GEM-TECH beam

An understanding and modelling of the failure mechanism and failure pattern for novel cementitious materials like the GEM-TECH material is essential for designing structures that would incorporate them. The actual ANSYS crack plot for the modelled GEM-TECH beams is given in Fig. 9. The crack plot shows consistency with the actual failure/crack pattern observed from experiments when both sets of beams were tested. The inclined cracks due to shear at the shear span (shear-flexure segment) of the beam between the load and support positions was dominant over the vertical cracks due to bending moment at the centre region of the beam between the two load points. The tiny circles clustered at the support points and at the load points indicate crushing of elements around these regions.

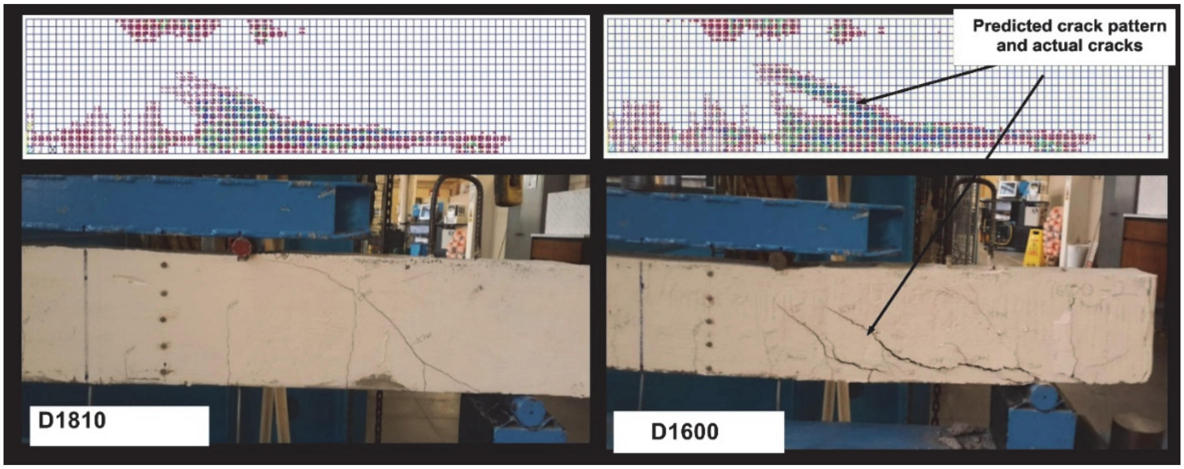

Fig. 9. ANSYS crack/crush plot for GEM-TECH material under flexural loading.

Even though the flexural crack tends to appear first when the GEM-TECH beam is loaded, they do not grow and migrate as fast as the shear cracks when they eventually appear. The GEM-TECH material contains millions of tiny air cells distributed within the material, and due to the fact that these air cells offers no resistance to shear, the crack tend to travel quicker. When cracks are prominent in a structural member, it disrupts its aesthetical features; excessive and deep cracks would negatively affect the durability of the material. According to Kumar et al. (2007), these cracks and their migration is influenced by the reinforcement ratio of the beam and its flexural strength capacity. Based on the FEA simulation of the GEM-TECH material under flexural loading, two main failure patterns were outstanding; local crushing at regions of high concentration of compressive stresses and diagonal shear failure.

4. Conclusion

In this study, an FEA model was developed using ANSYS to simulate and fully understand the behaviour of reinforced beam made with GEM-TECH material. The results for FEA model was compared with results from reinforced beams made from GEM-TECH material tested in the laboratory under four-point loading test. The following main points were deduced from the study;

- The finite element model using ANSYS software makes a direct contribution to predicting the structural behaviour, performance and failure mode of the GEM-TECH material which results in a good agreement with available full scale experimental results and observation for different design densities of the GEM-TECH material.
- The comparison of the failure load and deflection values for FE model and experimental model showed good agreement. The failure load recorded from experiments all fall within 10% range of the predicted failure load from FEA. The maximum load for the FE model, however, was approximately 15% greater than analytical maximum load, with a slightly steeper load deflection plot than that from experimental plot. This can be attributed to the assumption of a perfect bond between the GEM-TECH material and steel reinforcement bars, and neglecting the minor defects that may have been present in the experimental samples.
- The GEM-TECH material showed a good flexural response from the FEA, however, the material offers less resistance to shear as compared to flexure. Crack/crush plot shows that the reinforced beam made from GEM-TECH material subjected to flexural loading will most likely fail as a result of either local crushing resulting from a high concentration of compressive stresses or diagonal shear failure resulting in inclined cracks within the shear arm that propagates faster upon appearance. This is because of the loss of aggregate interlock from coarse aggregates as in normal weight concretes.

- Reinforced GEM-TECH beam, based on results from FEA carried out in this paper, is best suited in areas where the loads are evenly distributed and therefore, reduced stress concentration that could result in local crushing of the material. For efficient use of GEM-TECH beams, sufficient shear reinforcement must be provided to curb propagation of diagonal cracks in the GEM-TECH beam.

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