Modelling reinforced concrete coupling beams designed for low-to-moderate seismic regions

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Abstract

Reinforced concrete (RC) coupling beams are often used to transfer and resist the earthquake loads. Because of their importance, some experimental and modelling research has been conducted focuses on these important elements. While their behaviour is known to be different from that of conventional beams, in low-to–moderate seismic regions, such as Australia, coupling beams are often designed as an “ordinary beam” with standard longitudinal reinforcements and stirrups. This incorrect procedure may be potentially dangerous and lead to a premature and brittle failure in the event of an earthquake. A finite element modelling approach, which also considers the non-linear behaviour of the beam, is investigated, with the aim of obtaining a realistic and useful model for future research projects and new design procedures. This paper presents the preliminary investigations for using finite element modelling to predict the response of coupling beams with ordinary detailing. The focus of this preliminary study is to determine and recommend an ideal element sizing to model these types of coupling beams by using a mesh sensitivity analysis. The results of some finite element modelling analyses are compared to some experimental results. Furthermore, a RC coupling beam with transverse penetrations, which is common in Australia, is analysed here.

Keywords: coupling, beams, lintel, seismic, shear, transverse, penetrations

INTRODUCTION

Reinforced concrete (RC) structural walls are used in Australia and other low-to-moderate seismic regions as the primary lateral load resisting elements in a building. In a coupled-wall structure (Figure 1a), coupling beams (Figure 1b) are used to join the wall segments together in an attempt to effectively transfer and resist the lateral loads from wind and earthquake actions. Due to non-structural considerations, such as inter-storey building heights, short and relatively deep coupling beams are typically formed between the walls (Gurley, 2007; Kwan & Zhao, 2002). In Australia, a coupling beam is designed according to the conventional procedures of ordinary beams in the Concrete Structures Australian Standard AS 3600:2018 (Standards Australia, 2018). This is inadequate and potentially dangerous, as deep and short coupling beams have been shown to behave differently in comparison to ordinary beams (Galano & Vignoli, 2000; Paulay, 1971; Tassios *et al.*, 1996) and have demonstrated poor seismic performance in past earthquake events (Berg & Stratta, 1964; Mitchell *et al.*, 1995). While some building codes internationally require diagonal reinforcement in short and deep coupling beams, there is no such requirement in building codes for Australia and other low-to-moderate seismic regions. Detailing several transverse penetrations ("structural voids") through the web of the coupling beam is typically practiced by designers in Australia to allow for mechanical services at each floor of the building. However, there are currently no specific reinforcement detailing guidelines provided by the Australian Standards for this and the voids through the beam could seriously affect the structural performance of the beam itself in the event of the building being subjected to large lateral deformations. To date, no research has been conducted to investigate the seismic performance of coupling beams that (i) are detailed to current construction practice in Australia and (ii) have transverse penetrations.

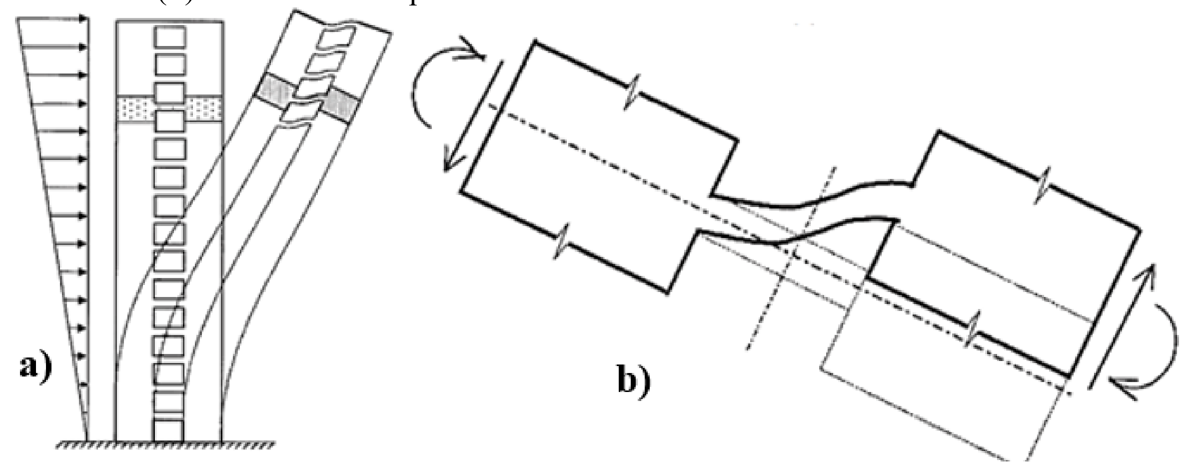

Figure 1 Idealised deflection pattern of a coupled-wall system (a) deflection of two coupled walls; (b) deflection of a coupling beam (Kwan & Zhao, 2002)

There have been relatively few experimental programs that have focused on the seismic performance of short and deep coupling beams detailed with conventional reinforcement layouts (e.g., Paulay, 1971; Tassios *et al.*, 1996). Moreover, as discussed in Kwan and Zhao (2002), the methods used to test these beams do not necessarily correspond to the loading conditions that coupling beams within buildings would actually be subjected to. Instead, the experimental research program from Kwan and Zhao (2002) used a loading procedure that better represented the actual conditions experienced by coupling beams. However, the reinforcement layouts and the mechanical properties of the reinforcement used for the beams tested by Kwan and Zhao (2002) differ in comparison to coupling beams designed in Australia. Furthermore, Galano and Vignoli (2000) tested short and deep coupling beams using a similar loading procedure to that in Kwan and Zhao (2002), but only four of the sixteen specimens that were tested had conventional reinforcement typical of Australian detailing practice.

The authors have had some discussions with some senior structural engineers from different large consulting firms in Australia. Some of the findings indicated that a typical design depth for coupling beams, or "lintel beams", was 1800 mm in some cases, with a corresponding typical length of 1000 mm; these values are also consistent with those given in Gurley (2007). This results in a shear span ratio of approximately 0.275, whereas the lowest shear span ratio of a coupling beam that has been experimentally tested with convention reinforcement layouts has been 0.50 (Tassios *et al.*, 1996). Furthermore, discussion with practicing engineers have revealed that it is common practice in Australia to penetrate several transverse openings through RC coupling beams to allow for services (Figure 2). Whilst there are some guidance and requirements for detailing an ordinary RC beam with transverse penetrations in some international building codes (e.g. ACI-318), there is no such guidance in the Australian Standards. Transverse penetrations through coupling beams, which perform very differently to conventional beams, could seriously affect the structural integrity of the element in the event of an earthquake. Transverse penetrations through the beam are particularly worrying for the coupling beams described above, with very low shear span ratios (< 0.50), which are shear critical. While there has been some experimental research focusing on the performance of simple beams with transverse penetrations (or "web openings") (Yang *et al.*, 2006), no studies exist that focus on the seismic performance of coupling beams with such openings, which is common practice in Australia.

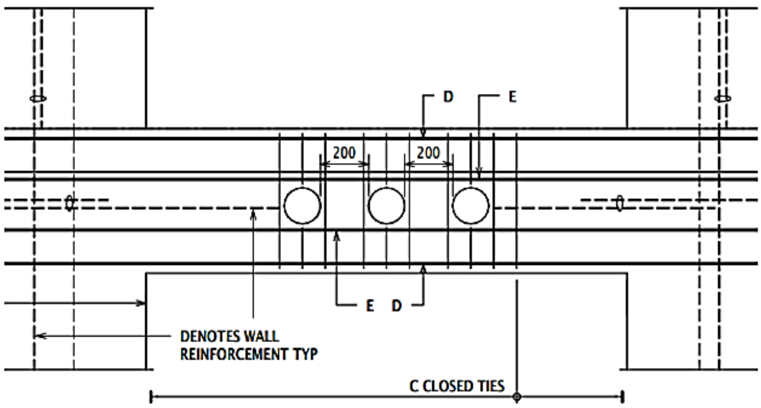

Figure 2 Coupling beam with web openings, typical in Australian construction practice

There has also been a paucity of research investigations using non-linear finite element analysis software (NLFEA) to predict the performance of RC coupling beams. Zhao and Kwan (2004) used NLFEA software for the nonlinear behaviour analysis of a series of beams, which had already been tested in the laboratory in a previous research (Kwan and Zhao, 2002). The comparison between experimental and numerical results shows some discrepancies with regards to the force-displacement relationship and therefore two main modelling problems were presented by Zhao and Kwan (2004): (i) the smeared reinforcement model used does not permit modelling of the pull-out of reinforcing bars, and (ii) an inaccurate cracked concrete stiffness model ignoring strain localisation and tension stiffening should be avoided. These two inaccuracies in modelling the beams lead to a much larger peak force in comparison to the theoretical (i.e., experimental) load-deflection curve and incorrect post-peak behaviour, examples of which are shown in Figure 3.

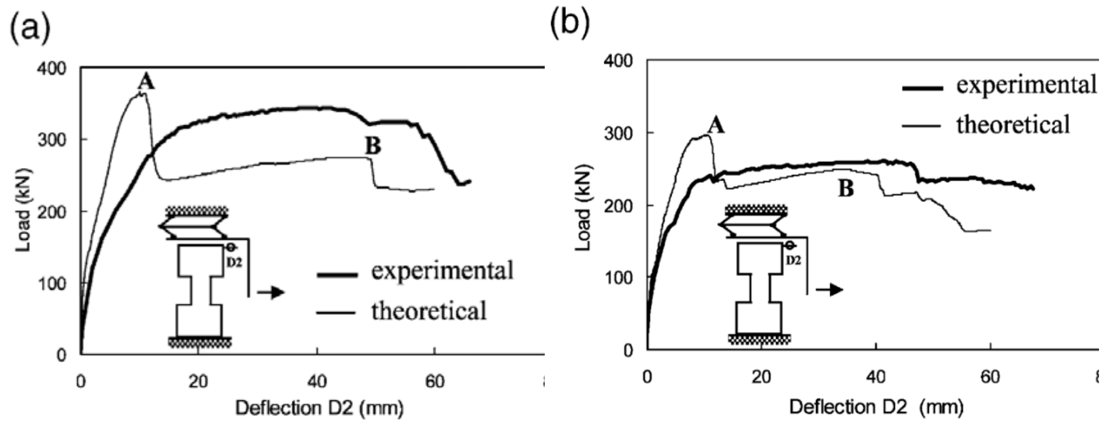

Figure 3 Force-deflection relationships predicted from nonlinear finite element modelling (i.e., theoretical) compared to experimental results from Kwan and Zhao (2004), showing the inaccurate peak force obtained

The focus of this research is to investigate if state-of-the-art finite element modelling software has the potential to model the complicated behaviour of short and deep RC beams in double curvature, which would be designed to the current Australian practice (i.e., inferior design details in comparison to that found in regions of high seismicity). This paper presents some of the preliminary work undertaken, including a mesh sensitivity analysis to determine the ideal element size for modelling these types of coupling beams.

MODELLING COUPLING BEAMS IN VECTOR2

Vector2 (Wong et al., 2013) is a non-linear finite element analysis software (NLFEA) specific for plane two-dimensional reinforced concrete sections subjected to dynamics load or quasi-static conditions. It proposes a wide range of material models for better representing the various constitutive responses and mechanism and while is primary purpose is modelling reinforced concrete elements rather than different continuum materials types (e.g. steel, masonry, wood). Reinforcement can be modelled either as smeared within the solid elements, or as discrete bars using the truss elements. It is also possible to model the bar slip and adhesion loss, related to reinforcement elements. The software proposes a manual or automatic function for deriving the mesh structure structures and includes a library of quadrilateral elements (8 d.o.f.), triangular elements (6 d.o.f.) and truss bar elements (4 d.o.f.). The program has already been successfully used in other previously researches for simulate the behaviour of RC elements such as walls and beams and provides satisfying results (Hoult *et al.*, 2018).

A mesh sensitivity analysis was undertaken to understand the influence of the size of the elements used. The final aim of this analysis is to provide guidelines applicable to different deep and short coupling beams for modelling purposes, suitable for the structure analysed, leading to consistent results. The numerical model created here reproduces the first specimen tested by Galano and Vignoli (2000) with conventional longitudinal and vertical bars reinforcement shown in Figure 4. The cross section was equal to 400 mm x 150 mm. 8 bars Ø10 reinforced with two bars Ø6 in the central zone and Ø6 stirrups every 100mm constitute the beam reinforcement. To simulate the performance of a coupling beams, the idealized walls were constrained by steel rollers; this setup attempts to have equal rotation at the two ends of the beam specimen. It should be noted that this test setup is essentially flawed, as discussed in Kwan and Zhao (2002), particularly for the beam's performance post-crack. However, for the purposes of a mesh-sensitivity analysis, this setup is used for modelling due to its simplicity.

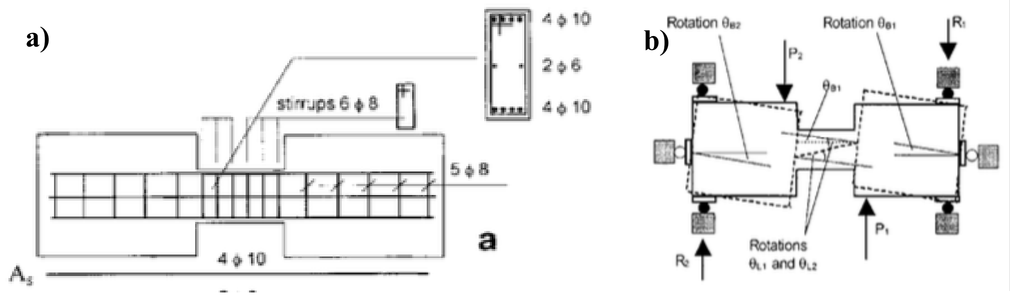

Figure 4 Specimen modelled in Vector2 (Galano and Vignoli, 2000)

A second model reproduces the first specimen tested by Tassios *et al.* (1996) with conventional reinforcement. The cross section was equal to 500 mm x 130 mm with two longitudinal reinforcement bars Ø12 and Ø8 stirrups every 75mm. The displacements were induced by means of an actuator at the specimen axis (i.e., centreline of the couple beam).

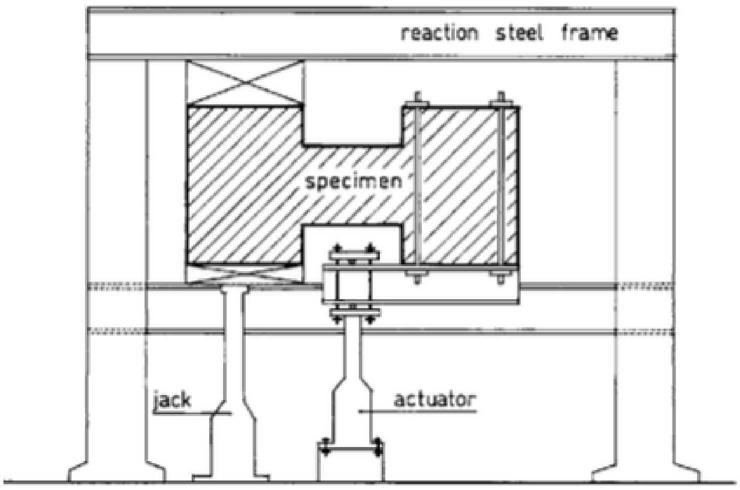

Figure 5 Specimen setup modelled in Vector2 (Tassios *et al.*,1996)

Based on the disturbed stress field model and the modified compression field theory, Vector2 uses a total-load iterative procedure, giving it numerically stable performance with good convergence characteristics. Second-order effects, such as compression softening, tension stiffening, shear slip along crack surfaces, and other mechanisms of cracked RC structures, are also considered in the model. Rectangular elements were chosen to model the concrete mesh. The maximum ratio between length and height is fixed at 1.5, as recommended in Palermo and Vecchio (2007). Truss elements are used to model longitudinal reinforcements and stirrups. A perfect bond between the concrete and the bar is assumed; while the author's concede that a perfect bond is not ideal, given the flaws previously discussed with modelling the behaviour post-peak, this initial study is focused on the mesh sensitivity and precision in simulating the peak force. The analyses were ran using a displacement-controlled procedure, where two prescribed displacements were used corresponding to the forces subjected to the beam experimentally (shown in Figure 4a and 4b). This method allows to also obtain the post-peak behaviour. In the context of the mesh sensitivity analysis conducted here, only the behaviour up to the peak strength is considered due to the various issues raised by Zhao and Kwan (2004).

The mesh size is changed uniformly over the whole structure. The aim is to define a size that is suitable for the general mesh and that can eventually be refined in critical areas, such as the joins between the wall beams, where the shear sliding failure should occur. The ratio α relates the thickness of the beam (t_b) to the size of the model mesh (s) and can be used to help indicate the ideal mesh size to use for these structural elements.

Table 1 gives the different mesh sizes used in VecTor2 to model beam specimen P01 from Galano and Vignoli (2000) and specimen CB-1A from Tassios *et al.* (1996). Furthermore, the ultimate shear force (V_u) determined by VecTor2 is indicated in Table 1 and is also illustrated in Figure 6 as a function of α. It should be noted that the V_u values have been normalised to the maximum shear force capacity of the beam observed experimentally ($V_{u.Exp}$) of 233 kN for P01 specimen and 221 kN for specimen CB-1A according to the previous researches. As indicated in Figure 6, α ratios between 0.25 and 0.4 gives reasonable and stable estimates of V_u from VecTor2 for this beam, within +/- 10% of that observed experimentally. Values of α outside of this range result in unrealistic peak shear force capacities compared to that observed experimentally. The large difference of shear force capacity estimated from VecTor2 emphasizes the need for a mesh sensitivity analysis prior to deriving reliable results using NLFEA.

Table 1 Different mesh sizes used in VecTor2 with corresponding maximum shear capacities

Element thickness	Mesh size	Ratio (α)	Maximum shear
[mm]	[mm]	-	V_u [kN]
150	25	0.16	207
150	37.5	0.25	244
150	50	0.33	248
150	62.5	0.42	249
150	75	0.50	271

Element thickness	Mesh size	Ratio (α)	Maximum shear
[mm]	[mm]	-	V_u [kN]
130	21	0.16	188
130	32.5	0.25	217
130	43	0.33	225
130	55	0.42	227
130	65	0.50	258

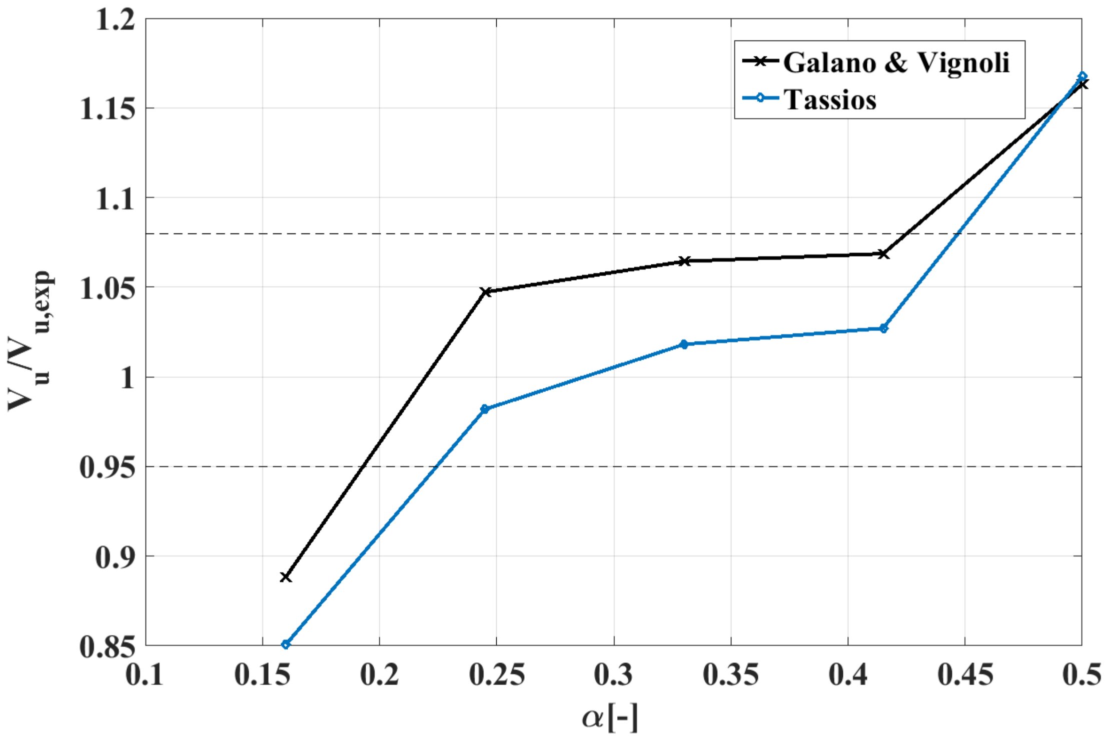

Figure 6 Details of test model and principal results of mesh sensitivity analysis

MODELLING BEAMS WITH TRANSVERSE PENETRATIONS

VecTor2 was also used to model a reinforced concrete beam with transverse penetrations. As stated in the introduction, coupling beams in Australia, commonly referred to as simply lintel beam, are typically designed with transverse penetrations to allow for services. To the author's knowledge, there has been no testing of beams with transverse penetrations subjected to the type of loading for a coupling beam. However, these has been some testing of RC beams with transverse penetrations subjected to single curvature bending [i.e., El Maddawy & Sherif (2009)]. Thus, a specimen from El Maddawy & Sherif (2009) will be modelled in VecTor2 for the purposes of determining the applicability of VecTor2 in modelling the performance of these types of beams. It should be noted that VecTor2 was also used to model this beam specimen in Liu & Mihaylov (2019).

Specimen NS-250-C from El Maddawy & Sherif (2009) was modelled in VecTor2 with transverse penetrations. The beam span was 1000 mm long and 500 mm deep with a thickness of 80 mm. Two square transverse openings were included in the beam with a size of 150 mm x 150 mm. Two mesh sizes were chosen for modelling purposes, where side lengths of the quadrilateral element sizes were 12.5 mm and 25 mm (Figure 7a and Figure 7b respectively). As observed experimentally by El Maddawy & Sherif (2009), the beam failed by a formation of two independent diagonal shear cracks in the opening chords shown in Figure 8.

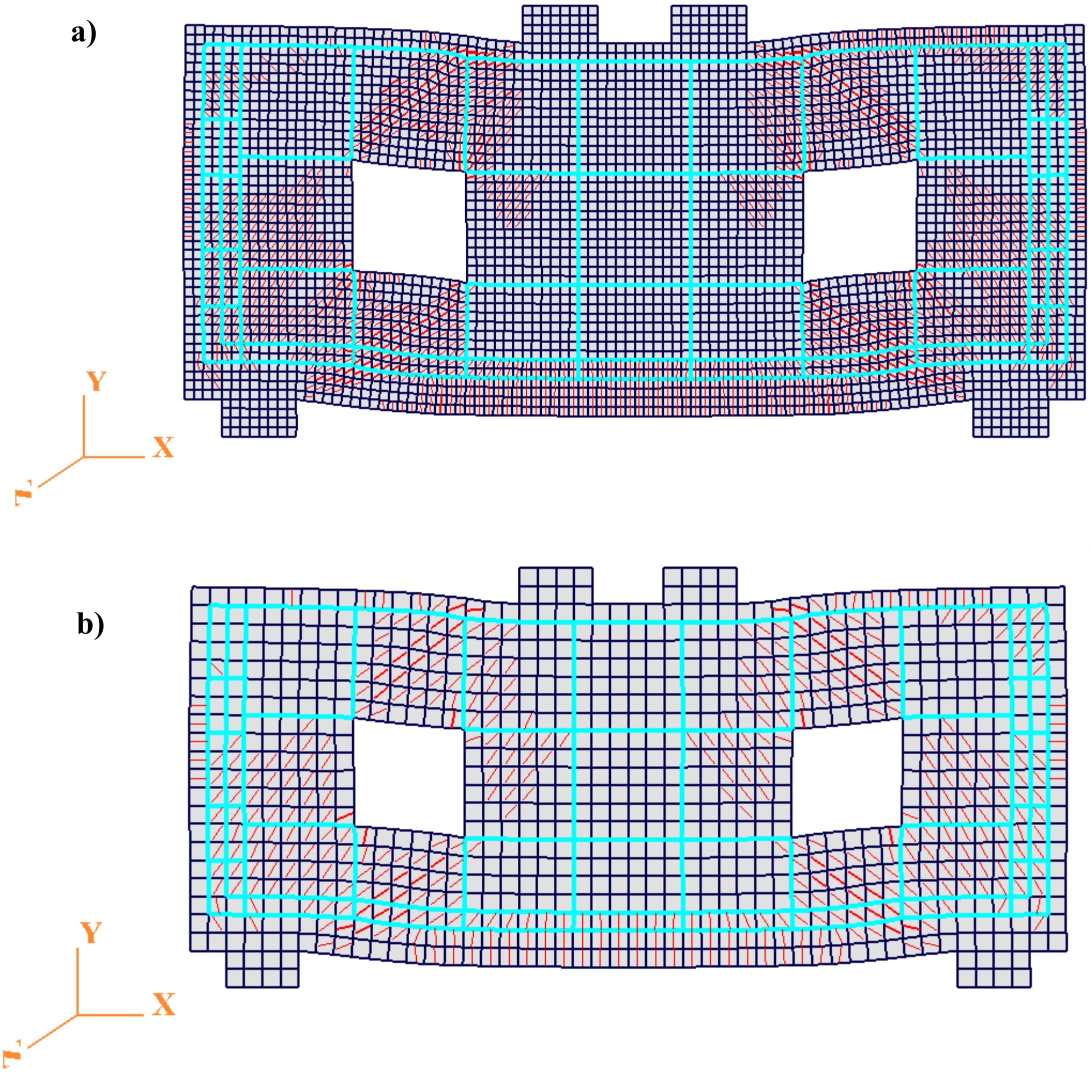

Figure 7 Cracking and deformation state of specimen NS-250-C from El Maddawy & Sherif (2009) from VecTor2 with element sizes of (a) 12.5 mm and (b) 25 mm

The force-displacement behaviour, as produced by VecTor2, is given in Figure 8 for both models. Superposed in Figure 8 is the ultimate force observed experimentally ($F_{u.exp}$) for this beam specimen. Interestingly, the VecTor2 model with an element size of 12.5 mm estimates an ultimate force capacity lower than $F_{u.exp}$, while the model with element sizes of 25 mm produces an ultimate force higher than $F_{u.exp}$, hinting that the ideal element size for modelling purposes and for this beam is somewhere in between. The α values for these mesh sizes, corresponding to the same definition as that given in the previous section, are equal to 0.16 and 0.31 for the 12.5 mm and 25 mm models respectively.

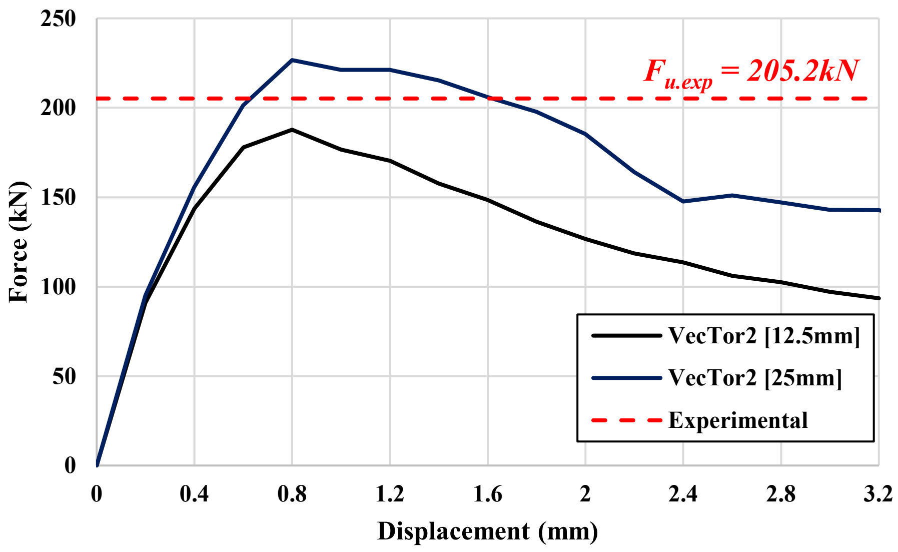

Figure 8 Force-displacement relationship as predicted by VecTor2

VecTor2 has been shown to produce reasonable results of the ultimate force for a beam specimen with transverse openings. The recommended alpha (α) values from the previous section, which modelled coupling beams, appears to be consistent with the mesh sensitivity results here. The next step in this research programme would be to model a beam with transverse openings in VecTor2 as a coupling beam and estimate its seismic performance compared to that without transverse openings.

CONCLUSIONS

Coupling beams are important elements in the structural resistance of seismic loads. These elements are not always given the right attention and their design is often inappropriate, especially in areas with low-to-moderate seismic risk. The purpose of this research investigation is to model the nonlinear behaviour of the coupling beams using the FE method. A validated model will allow the analysis of coupling beams with a range of parameters to determine their performance and new findings that will allow recommendations for future designs.

The mesh sensitivity analysis is the first step taken in correctly modelling and validating these types of beams. The vastly different force-displacement relationship that was observed numerically with the different mesh sizes used indicates the importance of an adequate choice of mesh prior to conducting any type of large-scale parametric study with any confidence of the result.

The results from VecTor2 here indicate that a mesh with a ratio of 1:3 between the element size and the thickness of the beam can replicate the force displacement behaviour measured from the experiment and is hence recommended. Anything different from this value can lead to an underestimation or overestimation of the maximum shear in the beam and can therefore not be completely representative of the coupling beam behaviour.

The next part of this research program will involve modelling the bond behaviour between the steel and the concrete using truss-link elements, which has been known to account for a large amount of the displacement (and rotation) capacities of these beams.

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