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Effect of Beam Design on Progressive Collapse Resistance of RC Framed Structures

Said Elkholy[1,2], Ahmad Shehada[1], Bilal El-Ariss[1,3]
[1]United Arab Emirates University
P.O.Box 1555, Al Ain, UAE
selkhouly@uaeu.ac.ae; 201970261@uaeu.ac.ae;
[2] Fayoum University
P.O. Box 63514, Fayoum, Egypt
sak00@fayoum.edu.eg
[3]corresponding author
bilal.elariss@uaeu.ac.ae

Abstract **-** This study presents numerical findings of an investigation into the effect of beam dimensions and sagging and hogging reinforcement ratios on progressive collapse response of reinforce concrete (RC) frame sub-assemblages when faced with an interior column loss. Also the flexibility of the beams in terms of height to span ratio which is directly correlated with compressive arch action and catenary action mechanisms is not directly emphasized. To this aim, four RC frame sub-assemblages of constant span lengths and different beam dimensions and reinforcement ratios were designed. Built on earlier calibrated numerical models using fibre element approach, nonlinear static push-down analyses capable of accurately simulating structural response to large deformations were performed for the four frame sub-assemblages with different beam designs. The study demonstrates that the beam design influence is significant as it completely changes the progressive collapse resistance and behavior of such frames while the beam span lengths are kept constant. Frames with small beam cross sections showed ductile behaviour due to catenary action, whereas frames with larger beam cross sections displayed brittle failure and predominate arch action.

Keywords**:** Progressive collapse; Beams; Arch Action; Catenary Action; Fibre element approach; Numerical simulation.

1. Introduction

Design guidelines on progressive collapse have been developed and introduced into design codes in the USA, UK, and Europe. These guidelines concentrated on incident control, enhanced local resistance, and providing alternate load paths to assure the prevention of a larger failure. In the latest edition of U.S. Design Guidelines (DoD 2016, GSA 2016 e.g. [1, 2]) recommendations are presented to limit non-proportional failures and few mitigation procedures have been proposed.

Knowing the difficulty and randomness of progressive collapse, significant researches on the topic have been conducted and resulted in substantial progresses in the field. Scott et al. [3] added an original integral procedure in the OpenSees software program to compute large deformations of structures. To improve the modeling process Lu et al. [4-6] generated a fiber-based program, THUFIBER, to better capture the catenary action phase in the reinforced concrete members behavior when subjected to dynamic loading. A quasi-static progressive collapse test was experimentally executed by Yi et al. [7] on a 2D frame to define the collapse mechanism and determine the frame collapse resistance. Yu et al. [8, 9] and Izzuddin et al. [10] examined progressive collapse behavior of framed structures due to a middle column removal by conducting a number of beam-column structure tests. Using test results from the literature, Li et al. [11, 12] derived the relationship between the catenary action during the progressive collapse and linear and nonlinear resistances of RC frames. Susceptibility of framed structures faced with a sudden removal of a corner column scenario was evaluated by Gerasimidis et al.[13-15] and a new analytical model to evaluate the stability of the structure was proposed.

The authors [16] presented a mitigating scheme to improve the structure strength to progressive collapse by providing appropriate ductility, continuity, and redundancy and numerically evaluated the strength using SeismoStruct software. The technique comprises introduction of unbonded external steel cables in each floor and attached to the beams at anchorage and deviator locations to bridge over a damaged column of any floor. The numerical results demonstrate the prospect of resisting progressive collapse of reinforced concrete structures by implementing the presented technique. In a recent work, the authors [17] developed a simple numerical model that uses few elements and properly selected model parameters to accurately predict the resistance of structures subjected to interior column removal with minimal computational time and effort. Design of the structural members affect directly the behavior of structures to progressive collapse [18]. Also, the beam end section and support conditions have a great influence on the resisting mechanisms of flexure action, arch action, and catenary action. The gravity of properly considering these conditions in the numerical analysis of progressive is highlighted. The resisting mechanisms generated in beams could also be influenced by the beam height to span ratio and the beam longitudinal reinforcement ratio. Their influence on the structure resistance to progressive collapse was also inspected by other researchers [19-22].

There is a need to underline the significance of the reinforcement ratio to the structure capability to develop substantial large deformations caused by abnormal loads. It is of high interest to assess the impact of this design parameter on the structure ability to initiate supplementary load-carrying capacity through arch action and catenary action mechanisms.

2. Design of RC sub-assemblage

Four RC frame sub-assemblages of constant span lengths and different beam dimensions and reinforcement ratios were first designed for serviceability and strength requirements. Then the sub-assemblages were numerical modelling to investigate the effect of beam dimensions, flexibility, and sagging and hogging reinforcement ratios on the sub-assemblage progressive collapse responses. The eight-story RC frame building shown in Figure 1 was considered in this study. The equivalent frame of one of the floor shown in Figures 1 was considered as the frame sub-assemblage, which was designed for reinforcements and later modelled numerically for progressive collapse. The frame building has four bays in each direction. The floor height is 3 m and all the bays have equal span length of 5 m. The floor slab has a thickness of 150 mm. The beams have a constant web width "b" equals to 150 mm and four varying height dimension "a" of 300, 400, 500, and 600 mm. Beam dimensions "a" and "b" are shown is Figure 1.

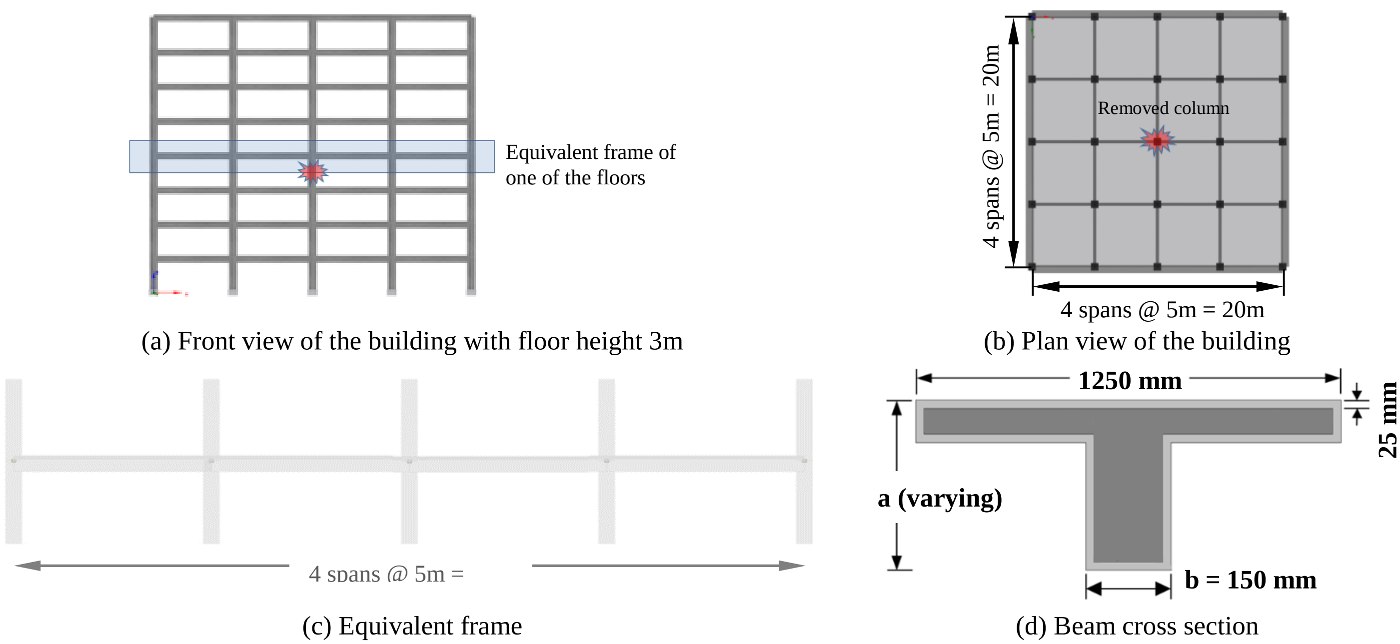


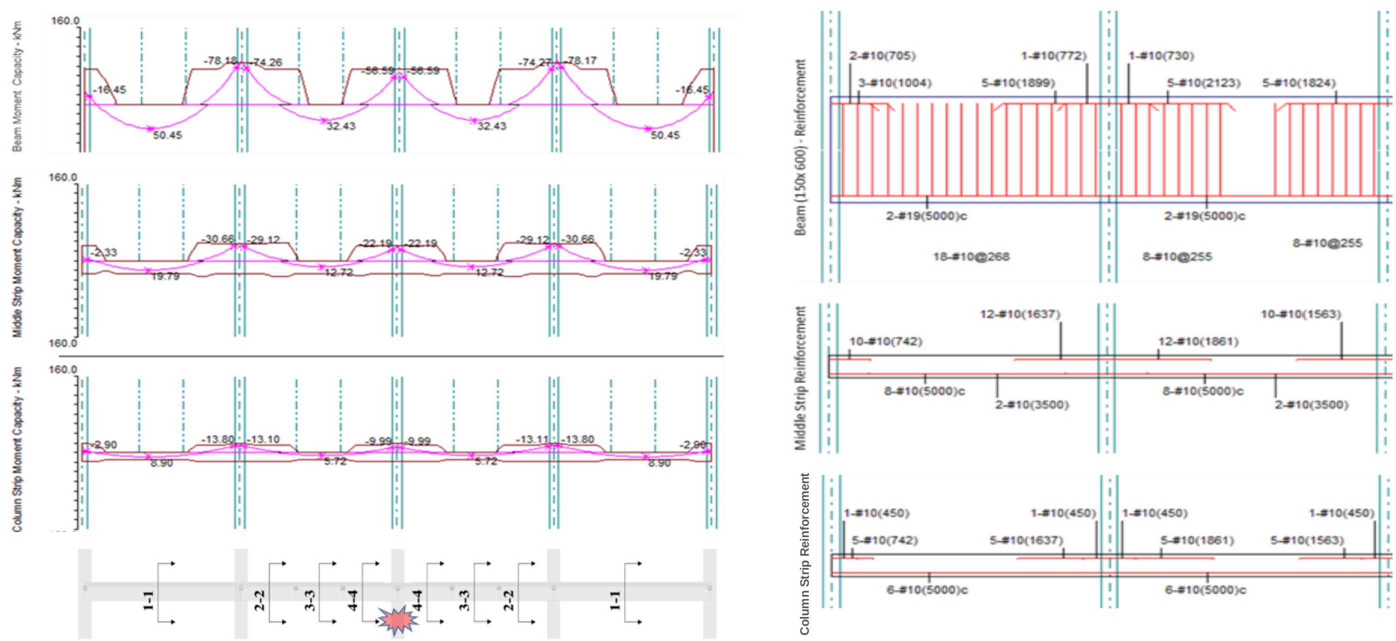
Fig. 1: Structural framing of the building and equivalent frame created for one of the floors

The material strengths used in this study are concrete compressive strength 30 MPa and yielding strength of web and longitudinal steel reinforcements 420 MPa. The two-way slabs and their supporting beams were designed for serviceability and strength requirements using SpSlab computer program. SpSlab program adopts the equivalent frame method as outlined in ACI 318-14 specifications and uses effective cracked sections for deflection calculations. The equivalent frame was considered in this study as the frame sub-assemblages which were modelled to simulate their progress collapse behavior due to interior column removal and with varying beam height “a”. The designs of the four RC sub-assemblages are summarized in Table 1. Sections 1-1, 2-2, 3-3, and 4-4 listed in Table 1 are shown in Figure 2. Table 1 demonstrates that as the beam height increased, the reinforcement ratio became less. Figure 2 also shows the analysis and the design, by SpSlab, of longitudinal sagging and hogging and web reinforcements for a beam height “a” of 300 mm, as an example.

Table 1. Design summary.

b × a (mm × mm)	**Reinforcement Detail**			
	Section 1-1*	**Section 2-2***	**Section 3-3***	**Section 4-4***
150 × 600	6 #10 Top	6 #10 Top	5 #10 Top	5 #10 Top
	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom
	#10 @268 Stirrups	#10 @255 Stirrups	#10 @255 Stirrups	#10 @268 Stirrups
150 × 500	7 #10 Top	7 #10 Top	5 #10 Top	5 #10 Top
	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom
	#10 @221 Stirrups	#10 @211 Stirrups	#10 @211 Stirrups	#10 @211 Stirrups
150 × 400	9 #10 Top	9 #10 Top	7 #10 Top	7 #10 Top
	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom
	#10 @81 Stirrups	#10 @173	#10 @173	#10 @173
150 × 300	3 #19 Top	3 #19 Stirrups	7 #10 Top Stirrups	7 #10 Top Stirrups
	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom	2 #19 Bottom
	#10 @62 Stirrups	#10 @120 Stirrups	#10 @120 Stirrups	#10 @62 Stirrups

*Sections 1-1 through 4-4 are at maximum sagging and hogging moments. Also see Figure 2a.



(a) Moments in slab and beam (b) Reinforcement detailing in slab and beam; due to symmetry half of frame is shown

Fig. 2: Analysis and design outputs by SpSlab - case of beam height “a”= 300 mm (“b”=150 mm).

The design of the four sub-assemblages with varying beam height “a” was examined to reflect on the impact of “a” on the concrete and steel quantities per one floor. Figure 3 shows that the effect of changing the beam height “a” on the material quantities is notable. As the beam height increased from 300 mm to 600 mm, the concrete volume per floor increased by 13% while the reinforcement weight per floor decreased by 11%. These variations in material quantities have a serious influence on the ductility and flexibility of the frame behaviour as well as on the cost.

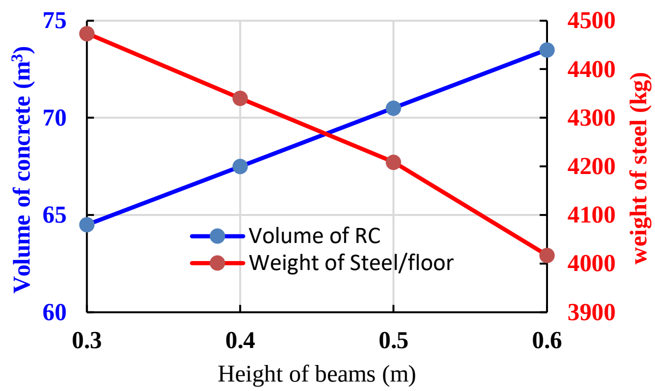


Fig. 3: Material quantity variation (per floor) with respect to beam height.

3. Numerical Modeling

Built on earlier calibrated numerical models [16, 17] using fibre element-based software, *SeismoStruct* [22], the four RC frame sub-assemblages designed in this study for serviceability and strength requirements were numerically modelled to investigate the effect of beam dimensions, flexibility, and sagging and hogging reinforcement ratios on their progressive collapse response. The numerical model utilized in this work was verified for accuracy by the authors in a previous papers [16, 17]. Test results reported by different researchers were used to calibrate and validate the efficacy of the model. *SeismoStruct* is utilize since it models and analyses structures subjected to large deformations as a result of column elimination. The members are modelled using beam-column element and material and geometrical nonlinear are considered. The member cross section modelled by discrete separate fibre elements (500-1000 in this study) representing concrete and steel. Inside the member cross section, the mesh size and grid number and are routinely created by the program according to the change in the compressive strengths of concrete due to the confinement of the section. The spread of plasticity along the element derives from an inelastic cubic formulation with Gauss points to use for numerical integration of the equilibrium equations, Figure 4. Nonlinear static pushdown displacement-controlled analysis was performed by applying the load at the removed column position to forecast the progressive collapse response of the sub-assemblage. The load was applied in increment and member material performance criteria were identified such as cracking and crushing in concrete, yielding and fracture of steel reinforcement, and failure of the element. With the fiber element approach, the load was incrementally increase until a performance criterion was reached or failure occured.

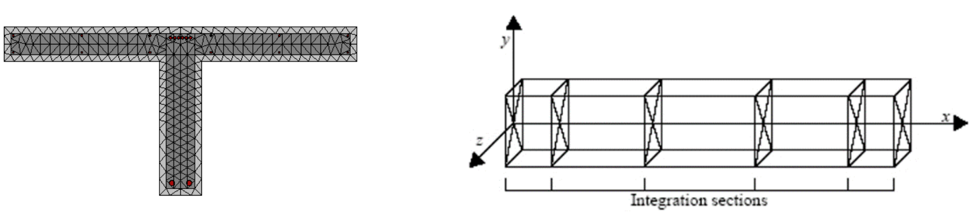


Fig. 4: Section discretization pattern and member integration section, *SeismoStruct* [23].

4. Numerical Results and Discussions

The load displacement curves of the RC frames are shown in Figure 5. The figure clearly shows that the beam dimensions and the corresponding sagging and hogging reinforcement have a direct influence on the progressive collapse response of the frame. Frames with beam height of 300 and 400 mm demonstrated a ductile behavior and a capacity to accommodate large deformations. This is credited to the increase in the hogging moment reinforcement, whereas frames with beam height of 500 and 600 mm showed sudden failure due to less reinforcement ratio.

Attributed to the horizontal resistance from the neighbouring undamaged members that are not directly impacted by the column removal, slabs and beams that have been carried by the removed column endured additional deformation due to compressive arch action up to an upright vertical deflection at which the neighbouring undamaged members could no longer provide enough restraint. Compressive arch action was effective at slight vertical deflections and large beam height. It is clear from Figure 5 that compressive arch action substantially increased the resistance to progressive collapse as the beam height increased and the reinforcement ratios decreased.

As the vertical deflection increased, it is evident from Figure 5 that the behavior of the members with less beam heights and more reinforcement ratios was more plastic than it was for members with larger beam heights and fewer reinforcement ratios, where the behavior was in transition mode from compressive phase to tension phase. This is attributed to the flattening of the compressive force as the arch action got into a transformation phase from compression to tension.

With large deformations taking place, the axial force from the horizontal resisting neighbouring undamaged members was transformed into a pulling tensile force, altering the member behavior during which strength was regained and deformations increased, as shown in Figure 5. This behavior is a ductile one and referred to as catenary action. The pulling tensile force hinged basically on the provided longitudinal hogging moment reinforcement ratio and its vertical component increased as deflection increased due to large rotation in the members. Therefore, the more the longitudinal reinforcement ratio is the larger the vertical tensile force gets leading to strength increase and more deformations. This is verified in Figure 5 where members with small beam heights and large reinforcement ratios (beams 150x300 mm and 150x400 mm) exhibited catenary action leading to large resistance and displacement. Consequently, these beams revealed more flexibility to effectively bear large deformations and resist higher load levels. On the other, members with large section height and less reinforcement ratio (beams 150x500 mm and 150x800 mm) did not display catenary action. On contrast, they displayed a brittle and sudden failure in the transition zone. This is accredited to the reinforcement rupture as the deflection increased due to more rotations in the members

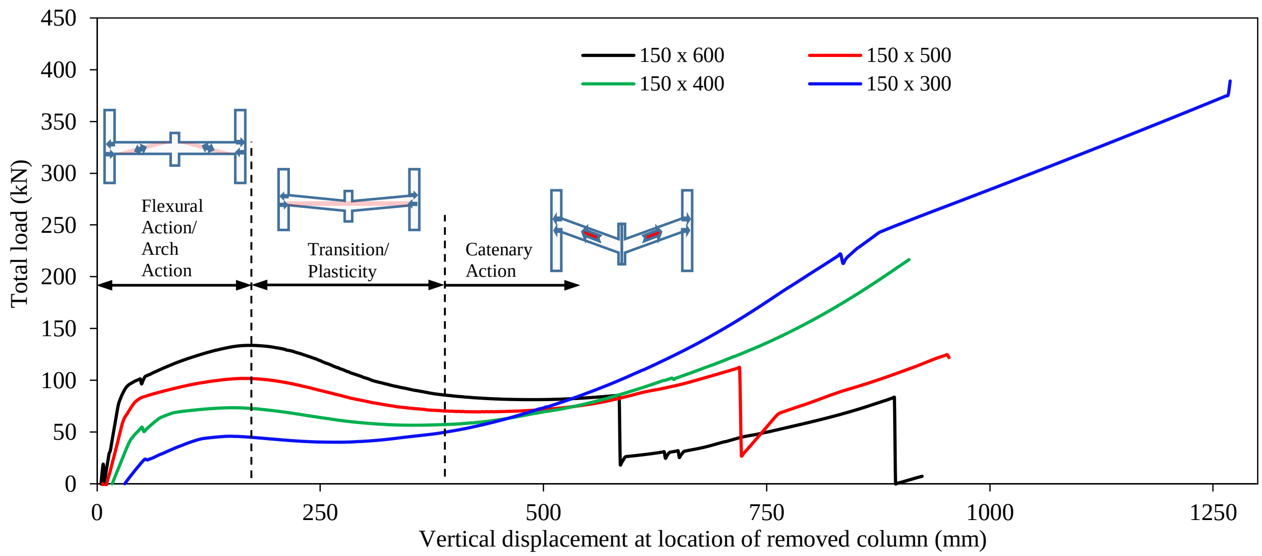


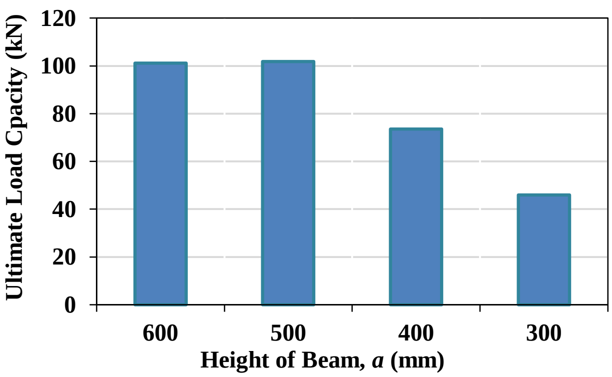
Fig. 5: Numerical load-displacement behaviour of the RC sub-assemblages

Figure 6 shows relations between ultimate load capacity, load at failure, maximum deflection, and total energy versus the height of the beams. The ultimate load capacity is the maximum load within the arch action phase.

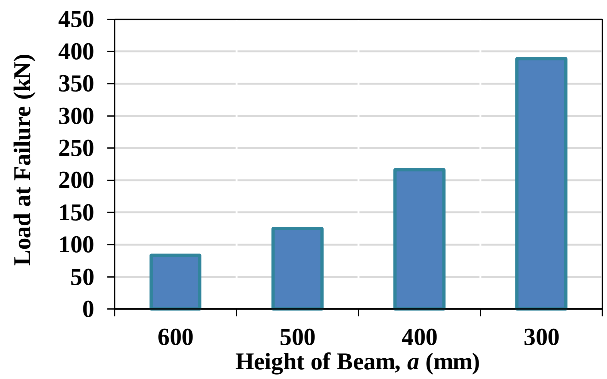
Figure 6a demonstrates that ultimate load capacity decreased as the height of the beam decreased. This is because the angle of the compressive strut during the arch action phase decreased with decreasing the beam height. This lead to a lesser vertical component of the strut compressive force to resist the loads. Whereas, the compressive strut angle increased with increasing the depth of the beam resulting in larger vertical force component and more resistance.

On the other hand, the load at failure in Figure 6b increased substantially with decreasing the beam height. This is attributed to the ductile behavior and beam flexibility as a direct consequence of increasing the negative moment reinforcement leading to a catenary action in the members that underwent large rotations and deflections associated with large vertical component of the tension force. The tension force increased since the negative moment reinforcement ratio increased when the beam section height decreased.

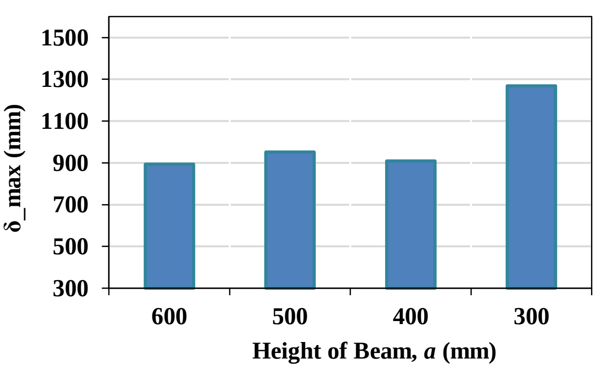
Figure 6c-d showed an increase in the maximum deflection (deflection at failure) and total energy as the beam height decreased. This is credited to the beams becoming more flexible and ductile as the beam height decreased supplemented with a reinforcement ratio increase.



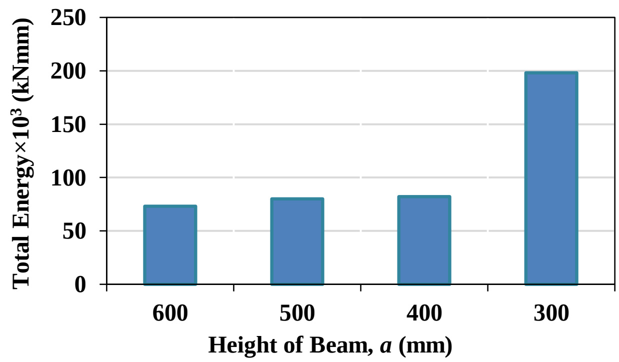
(a)



(b)



(c)



(d)

Fig. 6: Effect of the beam height on the sub-assemblage performance.

5. Conclusion

Numerical findings of an investigation into the effect of beam dimensions and sagging and hogging reinforcement ratios on progressive collapse response of reinforce concrete (RC) frame sub-assemblages when faced with an interior column loss were presented. The findings demonstrated that the beam height had a direct impact on the progressive collapse resistance of the sub-assemblage. In addition, as the beam height increased from 300 mm to 600 mm, the concrete volume per floor increased by 13% while the reinforcement weight per floor decreased by 11%. These variations in material quantities have a serious influence on the ductility and flexibility of the frame behaviour as well as on the cost.

Attributed to the horizontal resistance from the neighbouring members to the failed column, slabs and beams that have been carried by the removed column endured additional deformation due to compressive arch action. With large deformations taking place, the axial force from the reinforcement of the horizontal neighbouring members was transformed into a pulling tensile force, altering the member behavior into a catenary action phase during which resistance to progressive collapse was regained and deformations increased. This ductile behaviour and the increase in resistance and deformations were a direct end result of increasing the hogging moment reinforcement ratio.

The progressive collapse performance of the sub-assemblages considered in this study were critically affected by the horizontal member height and corresponding reinforcement ratios. The importance of the arch action and catenary action to increase the structure resistance to progressive collapse was demonstrated.

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