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NONLINEAR FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE TUBE IN TUBE OF TALL BUILDINGS

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Abstract: The non-linear finite element analysis (NLFEA) has potential as a readily usable and reliable means for analyzing of civil structures with the availability of computer technology. The structural behaviors and mode of failure of reinforced concrete tube in tube tall building via application of computer program namely COSMOS/M are presented. Three dimensional quarter model was carried out and the method used for this study is based on non-linearity of material. A substantial improvement in accuracy is achieved by modifying a quarter model leading deformed shape of overall tube in tube tall building to double curvature. The ultimate structural behaviors of reinforced concrete tube in tube tall building were achieved by concrete failed in cracking and crushing. The model presented in this paper put an additional recommendation to practicing engineers in conducting NLFEA quarter model of tube in tube type of tall building structures.

INTRODUCTION

Tube in tube concept in tall building had led to significant improvement in structural efficiency to lateral resistance. In its basic form, the system comprising a central core surrounded by perimeter frames which consists of closed spaced perimeter column tied at each floor level by spandrel beams to form a tubular structure. Usually these buildings are symmetrical in plan, and their dominant structural action take place in the four orthogonal frames forming the perimeter tube and in the central core (Avigdor Rutenberg and Moshe Eisenberger, 1983). Under the lateral load, a frame tube acts like a cantilevered box beam to resist the overturning moment and the central core acting like second tube within the outside tube. In order to get the more accurate result of analysis, the central core may be designed not only for gravity loads but also to resist the lateral loads. The floor structure ties the exterior and interior tubes together to make then act as a single unit and their mode of interaction depending on the design of floor system. No torsion effect was considered in this study, thus the floor system is effectively pin jointed to allow horizontal forces transmission before primary vertical structural elements of the building.

Combining shear wall and frame structures has proven to provide an appropriate lateral stiffening of tall building. As the shear wall deflects, shear and moments are induced in connecting beam and slabs which later induced axial forces in walls. The perimeter frame and the central wall act as a composite structure and deformed as in Figure 1. The lateral force is mostly carried by the frame in the upper portion of the building and by the core in the lower portion. The deflected shape has a flexural profile in the lower part and shear profile in the upper part. The axial forces causing the wall to shed the frame near the base and the frames to restrain the wall at the top.

The main purpose of this study is to predict the ultimate failure behavior of overall reinforced concrete tube in tube tall building. Hence, non-linear analysis has to be carried out in this study for better understanding of failure mode. Non linear analysis is a modelling of structural behavior to the ultimate state while linear analysis is a conventional analysis that does not pretend to be accurate (Aldo Cauvia, 1990). A sysmetrical tube in tube reinforced concrete tall building as shown in Figure 2, three dimensional (3D) quater model was implemented with finite element analysis method and take into account material non linearity.

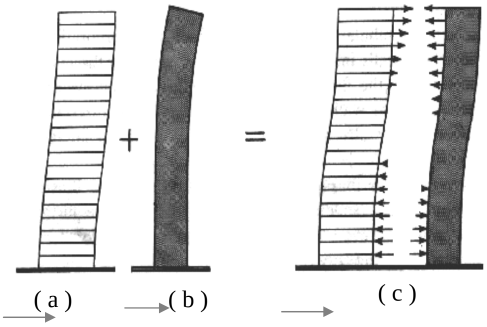
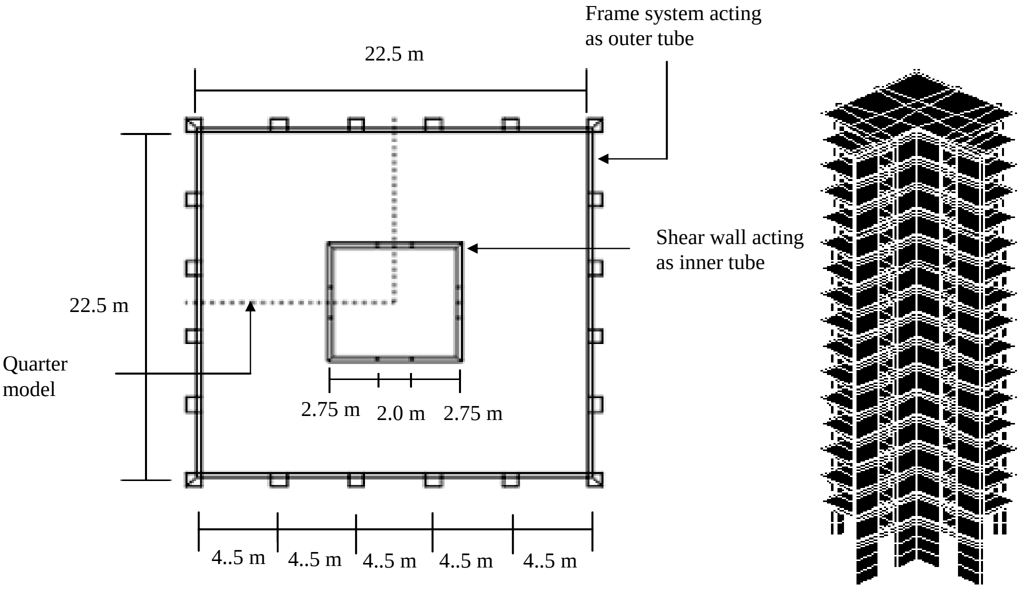


Figure 1 (a) Deform shape of frame; (b) Deform shape of shear wall; (c) Deform shape of combine frame + shear wall

METHOD OF ANALYSIS

Description of Model

The NLFEA model is a 16 stories reinforced concrete tube in tube tall building with typical storey height of 3.50m except ground floor is 6.0m heights. The full tube model is symmetrical in both axes in plan. The internal tube 7.50m x 7.50m is surrounded by perimeter frame tube 22.50m x 22.50m. All perimeter columns were arrange closely spaced at 4.5m center to center with the size of 0.90m x 0.90m from ground floor up to level 10 and 0.75m x 0.75m column after level 10. The spandrel beams are dimensioned 250mm thick and 750mm depth and tied to the perimeter column to form a perimeter tube. The thickness for slab is 175mm and presumed to act as a horizontal diaphragm to transfer the lateral load as well as vertical loads. The internal tube is formed by square perforated shear wall with the thickness of 350mm and the coupling beam is kept similar as thickness of the shear wall with the depth of 1000mm. COSMOS/M 2.0 (64K Version) finite element software is used to generate the model and perform subsequent non linear static analysis. For modelling idealization and domain discretization viability, only a modified quarter of tube in tube tall building is modelled in view of symmetrical and to cater limitation of COSMOS/M. After several attempts of NLFEA Run were performed out, the final model as indicated in Figure 2(b) was adopted as a final result in this study.



(a) (b)

Figure 2 (a) Plan view of full tube in tube type of tall building (b) 3D modified quarter model

Material Properties

All elements are represented by one element group i.e. 8 Node Isoparametric Hexahedral Solid elements associated with the material properties as indicated in Table 1. The values for of compressive strength for concrete, yield stress of reinforcement, concrete density, modulus of elasticity and Poisson's ratio conforms to BS BS8110: Part 1: 1995 and BS8110: Part 2: 1985. The concrete and reinforcementare assigned as one composite material with anmodified modulus of elasticity by assuming 1% of reinforcement for the structural element.

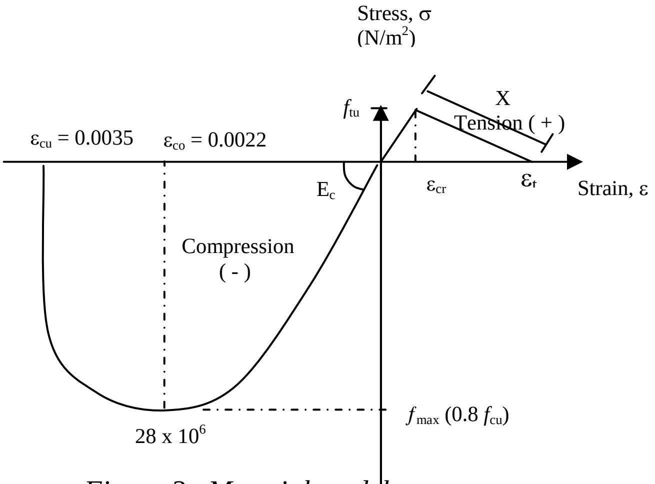
Table 1 Material

Parameter	**Property Value**
Compressive strength; f_{cu}	35 N/mm^2
Yield stress; f_y	410 N/mm^2
Modulus of elasticity; E	15.86 N/mm^2
% of reinforcement	1 %
Poisson's ration; ν	0.23
Density of concrete	2400 kg/m^3

Boundary Condition and Loading

The boundary conditions of the foundation were designed as all degree of freedom (all 6 DOF) while the boundary condition at the discontinuous edges of slab were assigning translation X. The velocity of wind load acting on the horizontal surface of the building is 44.44 m/s and the load is distributed uniformly along the surface from the bottom to the top of the building (CP 3: Chapter V: Part 2: 1972). The live loads of 3.0 kN/m^2 (BS 6399: Part 1: 1984) and dead loads of 5.40 kN/m^2 for slab distributed uniformly as vertical loads.

Properties of Concrete in Compression and Tension



X = Linear tension stiffening curve
f_{max} = Failure point in compression
f_{tu} = Failure point in tension (0.1$f$cu)
ε_{cr} = 0.1$f$cu / modulus of elasticity, Ec
ε_t = Tension stiffening

Figure 3 Material model

The nonlinear stress-strain relation adopted to represent the material model was according to BS 8110: Part 2:1985 as shown in Figure 3. The peak stress of 0.8 f_{cu} represents the maximum stress in concrete in uniaxial stress condition. The adopted compressive strain at maximum stress is 0.0022 and ultimate strain is 0.0035. The crushing condition is defined when ε_{cu} reaches the value specified as the ultimate strain and that material was assumed to lose its characteristics of strength and rigidity

Under tensile stress, concrete can be assumed as essentially linear until cracking occur at its tensile strength of 0.1 f_{cu} (Marsono, 2000). The interaction of rebar and concrete are simulated by introducing tension stiffening into the concrete model to simulate load transfer across cracks through the rebar (M.R.Chowdhury and J.C.Ray, 1995). The stress values were decreased linearly to zero after the cracking. Tension stiffening effect has significant influence on the nonlinear behavior of reinforced concrete structures. Thus using tried and converged method, tension stiffening is a part of parametric study in non-linear analysis. With reference to this material model in Figure 3, tension stiffening curve parameter can be search at 0.0002 upwards (i.e. greater than 0.00018).

Solution of NLFEA

The arc length method with iteration Modified Newton-Raphson (MNR) is used for the solution control of non- linear analysis. The analysis is required to reach the satisfactory solution parameters to accomplish the convergence. The parameter of the non -linear solution for this study as indicated in Table 2. During the load progressing, the analysis can terminate by controlling the maximum load parameter or the maximum displacement values. The maximum number of arc step in Table 2 is set to 50 since the actual arc step to complete the analysis to ultimate is not known initially. The initial load parameter is applied only at the first step of analysis then the next load parameter will be increased automatically by Modified Newton-Raphson algorithm. The convergence tolerance must be specified for the analysis between steps as an error of solution.

Table 2 Parameter

Parameter	**Value**
Maximum load parameter	1.0×10^8
Maximum displacement	0.2
Maximum number of arc step	50
Initial load parameter	0.1
Convergence tolerance	0.01

RESULTS

NLFEA Output and Interpretation of Results

Basically in the NLFEA of reinforced concrete tall building structure, the outputs of principal stress are used to present the failure of concrete structures in compression and tension. Concrete crushing is achieved when the values of minimum principal stress, P3 exceed the compressive strength (i.e. $0.8f_{cu}$) while concrete cracking is defined when the values of maximum principal stress, P1 reached the tensile strength (i.e. $0.1f_{cu}$). The tension cracking direction is assumed to be perpendicular to the direction of the principal stresses, P1 while the crushing direction is assumed to be perpendicular to the direction of principal stresses, P3.

Lateral Displacement

The load displacement response is presented in Figure 4. The maximum lateral displacement is 103 mm at node 2268, which located at the top level of model as indicated in Figure 7(b). The maximum load recorded is 59.17 KN at point A.

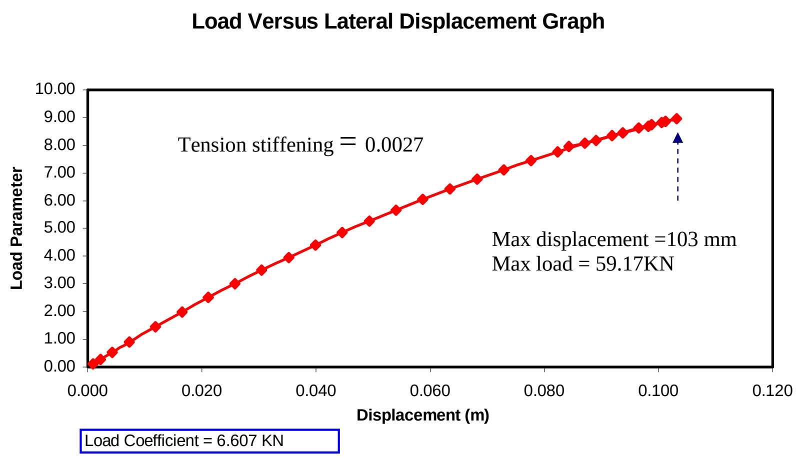


Figure 4 Load versus lateral displacement graph at Node 2268

Principal stress in shear walls

The contours of the principal stress P1 representing the maximum tension (+ve maximum) and P3 representing the maximum compression (-ve maximum). The crushing strength adopted in this model is $0.8f_{cu}$ = 0.8 x 35 =28 N/mm^2. Figure 5(a) clearly indicates the shear wall start to crush at the corner of shear wall base (node 2286) with the compression stress of 28.45 N/mm^2 (i.e. greater than 28 N/mm^2).

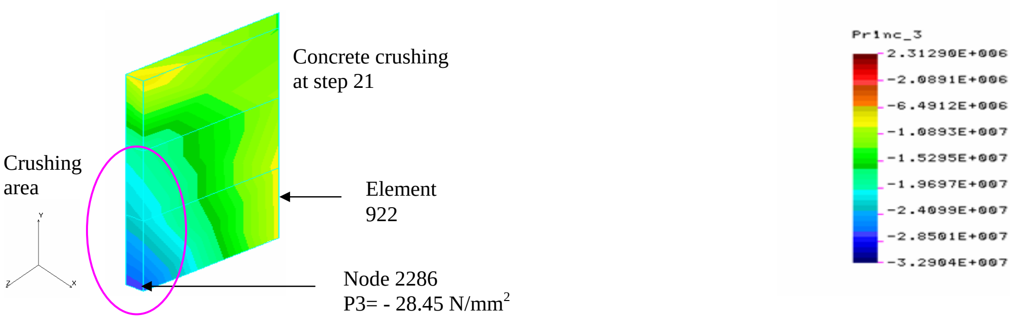
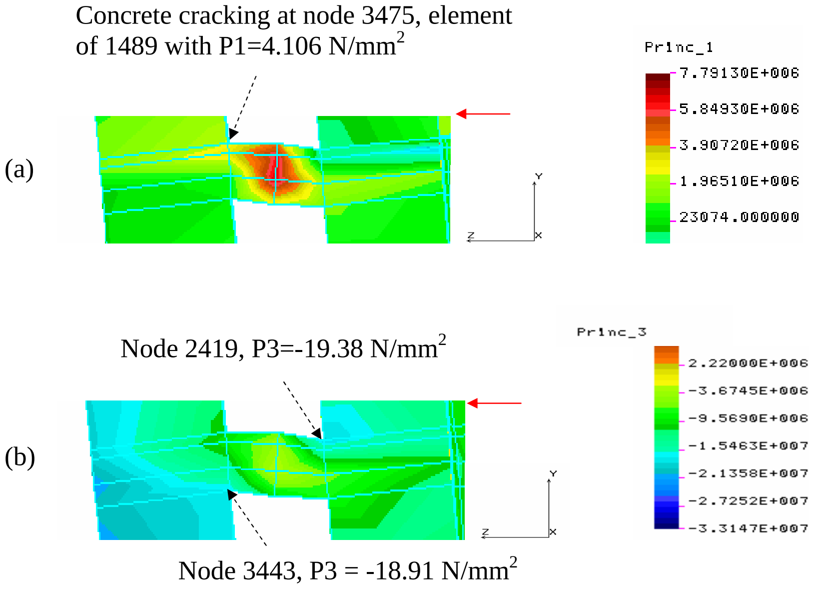


Figure 5 Minimum principal stress contour diagram at the part of shear wall base during concrete crushing at step 21

Principal stress in coupling beam

The stress contour and the deformed shape of coupling beam at level 1 are presented in Figure 6. The concrete cracking occur at the tension corner, node 3475 of element 1489 since step 15. The principle stress P1 was recorded at 4.106 N/mm^2 which exceed 0.1$f$cu = 3.5 N/mm^2. It is a clear indication of the tension contour was induced diagonally at the mid span of coupling beam. Another observation is the compression stress at both corners of coupling beam was increased by increment of steps until the analysis terminated at step 32, the maximum compression stress achieved is 19.38 N/mm^2 which is lesser than the crushing stress, 28 N/mm^2.



Step 15
Diagonal tension evident at the mid span of coupling beam. Cracking failure reached.
(P1 > 3.5 N/mm^2)

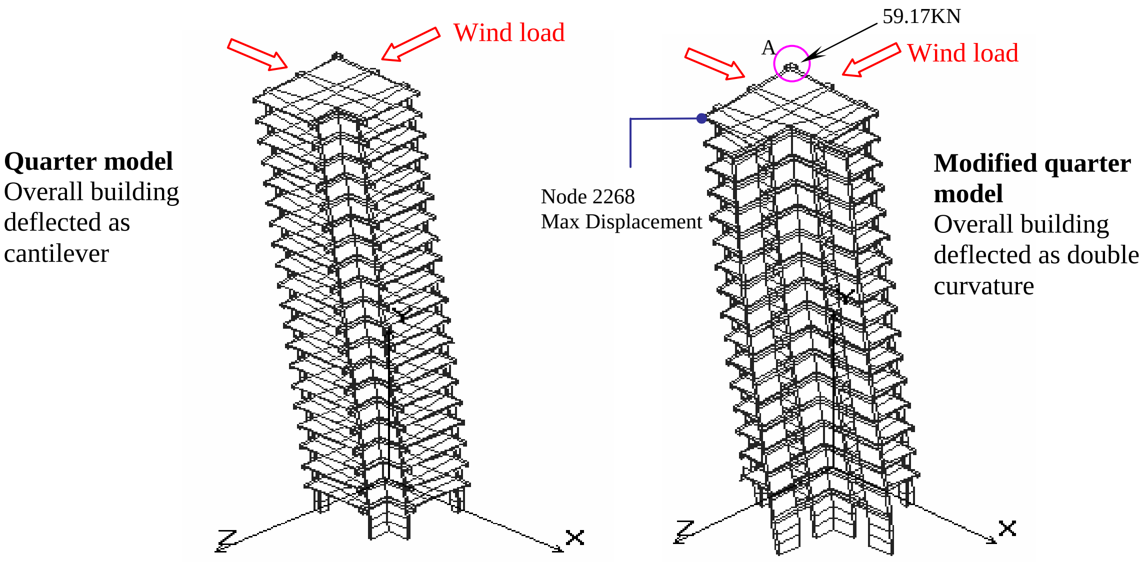
Step 31
Maximum compression of coupling beam at corner.
(node 2419 & node 3443)
Crushing failure was not occur in coupling beam.
(P3 < 28 N/mm^2)

Figure 6 (a) Maximum principal stress contour for coupling beam at level 1;
(b) Minimum principal stress contour for coupling beam at level 1

DISCUSSION

Overall building behavior

The modified quarter model had improve the deform shape of overall tube in tube tall building as shown in Figure 7. The deformed shape yields double curvature deflections, which resemble a deformed shape of combine frame and shear wall.



(a) (b)

Figure 7 (a) Deformation of quarter model (b) Deformation of modified quarter model

The presented failure modes of tube in tube tall building had proved that the overall model behavior is definitely control by compression failure rather than tension. With the evidence of the principal stress in the critical compression zone indicating crushing occur at the shear wall base, thus the overall mechanism of the structure had successfully leads the model to achieve its ultimate capacity at step 31. The stress contour by means of minimum principal stress for overall modified quarter model at step 31 is presented in Figure 8. Compression zone was located at the shear wall and perimeter column.

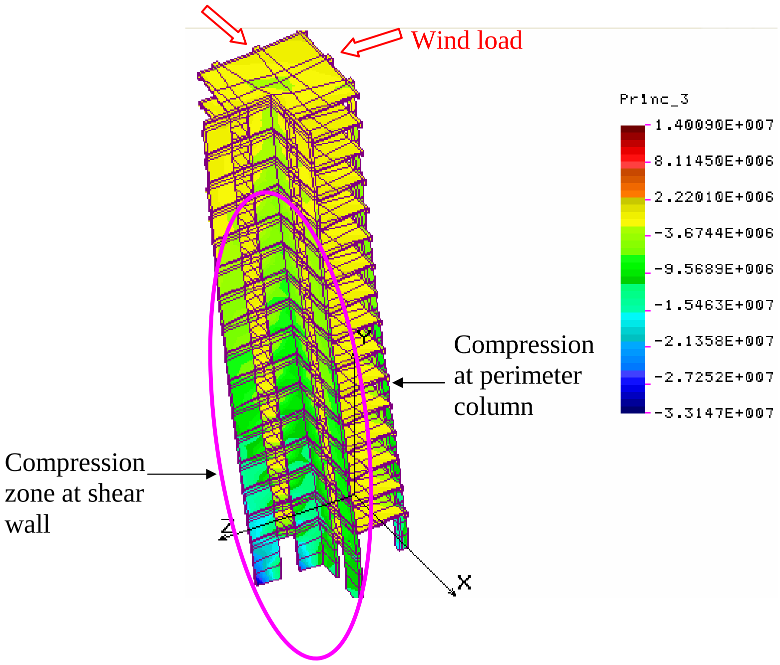


Figure 8 Minimum principal stress contour of the overall modified quarter model at step

Coupling beam and shear wall

The results indicate that the shear diagonal splitting mode of failure is happening for all coupling beams throughout the height. Even though there is a small flexural crack evident at the corner of coupling beam. The crushing of concrete at the shear wall base completes the final failure. It is showing that the total beam strength greater than wall strength. This may be due to oversize of coupling beam relative to the size of shear wall. The reduction in beam thickness may be lead to concrete crushing failure. Practically, the preferred mechanism of failure for perforated shear wall is that the coupling beams achieved the failure first before the shear wall. It is recommended that the beam should fail first followed by the wall; so that the load or vibration can be observed by the beams damaged section.

CONCLUSION

The NLFEA to ultimate stage using COSMOS/M Finite Element software on the 3D modified quarter model was successfully carried out. The analysis was able to capture all the nonlinear behavior as the load progressing. However, a refinement to the model may be carried out such as refining the FEA parameters and thus verifying the result with the lab experimental results wherever possible. The findings of this study can be summarizing as follow: -

(i) The quarter model is capable to perform non-linearity behavior up to ultimate limit state.

(ii) Modified boundary condition by assigning restraint at X-direction at all slab edges, fully restraint at wall bottom ends is considered appropriate in generating a double curvature profile as expected in tube in tube model.

(iii) NLFEA in tube in tube building perform well using non-linear concrete stress-strain curve up to 32 steps of non-linearity and yield the ultimate behavior of tall building.

(iv) Modified quarter model, which include the full configuration of shear wall, is found to be appropriate in modeling the tube in tube tall building as a quarter section. Thus, the behavior of coupling beams was successfully presented out.

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