Analysis of Alternate Load Path Method of Modular Structures

Pooja Nair[1], Prabha C[2]

[1] Pooja Nair, M.Tech Student, Department of Civil Engineering, Mar Athanasius College of Engineering, Kothamangalam
[2]Prabha C, Professor, Department of Civil Engineering, Mar Athanasius College of Engineering, Kothamangalam

---

Abstract - *In recent times, modular buildings and its construction has gained significant importance due to its increased advantages over conventional construction practices. But the need for studying the structural robustness of modular and prefabricated buildings is still a major research gap. Out of many methodologies, the project deals with alternate load path method to identify the failure mechanism. The aim of the project was to carry out ALP analysis and to find out alternate paths through which the loads redistribute. The work also included determining the Von Mises stresses and structural response curves for different module loss scenarios. The model was analyzed using the ABAQUS software where the whole model was meshed into finite elements for analysis. The model underwent a dynamic explicit analysis where it provided with stress distribution and deflection contours and time history graphs for force and displacement.*

Key Words: Progressive collapse, alternate path, load redistribution, modular buildings, inter-modular connections

1. INTRODUCTION

Over lately, the construction industry, modular buildings and its construction has gained significant importance owing to its advantages like safer and faster construction processes, better estimation of time and cost, less or no wastage of resources and lesser number of workers required at the site. In this form of construction, off-site factory-made volumetric units (called modules) and components are transported and assembled on-site to form an entire building. These units can be continuously supported, corner supported or non-bearing modules. The modules can be connected by rigid, semirigid or flexible connections.

The analysis of the structural robustness of the modular and prefabricated buildings has not been a great matter of study. But it is very important to analyze the failure mechanisms of modular buildings since they are more vulnerable to any kind of abnormal loading condition. If the damaged structure cannot attain equilibrium after the local damage has occurred, they can lead to progressive and ultimately global collapse of the structure.

To ensure that structural systems have adequate resistance to progressive collapse, most of design guidelines use the alternate path method (APM) or similarly alternate load path method. The alternate path method (APM) can be applied to study the gravity induced progressive collapse of modular steel buildings under entire module loss scenarios.

2. MODULAR CONSTRUCTION

Modular construction can allow for up to 95% of a building to be prefabricated in a controlled factory environment. This offers faster and safer manufacturing with better quality control, and reduces environmental impacts compared to traditional onsite construction. There is an increased demand for understanding the sensitivity of modular structures to local damages as the modular buildings are more vulnerable when subjected to extreme events.

Modular building is a construction technique whereby building modules are prefabricated off-site. It is a type of off-site fabrication referring specifically to volumetric units which may be a structural element of a building. Modular building refers to the application of a variety of structural systems and building materials, rather than a single type of structure. Prefabrication at offsite leads to a reduced overall construction schedule, improved quality, and reduced resource wastage but there is a lack of design guidance and can have relatively small structural spans due to module transport limits. The focus is on steel framed modules rather than concrete and timber frame modules, not for lack of importance, but for lack of recent research into the structures. For inter modular connections bolted connections are preferred over on-site welding of the modules. Due to the nature of modular construction, modular buildings exhibit some distinctive structural characteristics, particularly in those assembled with steel-framed units. Normally, such structures are designed to withstand not only the normal loading scenarios as in conventional buildings, but also the racking actions during transportation and craning, which are structurally more demanding. The load transfer between adjacent modules may occur mainly through the module corners. These features can potentially disadvantage structural robustness in design.

3. PROGRESSIVE COLLAPSE

Progressive collapse phenomena define as the failure of one or more key load-carrying elements either accidentally or intentionally which leads to the collapse of the entire structure or portion of it. The main reasons for progressive collapse refer to extreme loading like blast, bomb gas, severe earthquake, fire, vehicle or aircraft impact or design and construction errors. The progressive collapse takes place when one critical member is removed, and the load carrying by that member is transferred to the adjacent intact member through flexural elements. If the transferred load is more than the capacity of the nearby elements it fails and the process goes on till the whole building collapse entirely or partially. In order to avoid progressive collapse, the building should be designed with adequate integrity or structural robustness to develop alternative load paths such that additional loads from local damaged areas redistribute themselves to unaffected members. For modular buildings, the removal of a single load-bearing member may not lead to a progressive collapse of the entire building due to the high redundancy of structural elements

4. ALTERNATE LOAD PATH METHOD

The APM is an event-independent methodology that considers building system response after the triggering event has destroyed critical structural members. If one structural component fails, and appropriate alternate paths are available for the redistributed load, then general collapse does not occur. In the alternate load path method, the design is such that the building is capable of bridging over a removed structural element and that the resulting extent of damage does not exceed the damage limits. This method is used to evaluate structural robustness by examining the ability of a building to remain stable without violation of an allowable collapsed area, after removal of supporting elements.

An alternate load path analysis may be performed using one of three procedures: nonlinear dynamic, nonlinear static, or linear static. In the dynamic APM, the entire building is first gravity loaded in the presence of all modules. In case of module loss, they vibrate around a new equilibrium position by a large redistribution of forces, that do not exceed the capacity of primarily intact connections.

5. ANALYSIS USING ABAQUS/CAE

Abaqus/CAE, or "Complete Abaqus Environment is a software application used for both the modelling and analysis of mechanical components and visualizing the finite element analysis result. Abaqus/CAE is capable of pre-processing, post-processing, and monitoring the processing stage of the solver. Abaqus can solve complex civil engineering problems like multi-purpose problems, nonlinear dynamic problems, and changed boundary conditions. The software has basically two kind of solvers- Abaqus standard is best for linear/nonlinear static, linear dynamic, low-speed nonlinear dynamic and when unknown values at a later time are found by solving equations involving current values as well as later values. Abaqus explicit is best for high-speed dynamics, large deformations, and damage modelling and when the unknown values at a later time are found using current time values (already known). Complete finite-element analysis in ABAQUS software consists of 3 separate stages: pre-processing or modelling (cae file), processing or finite element analysis, post-processing or generating a report, image, animation, etc. from the output file (odb file).

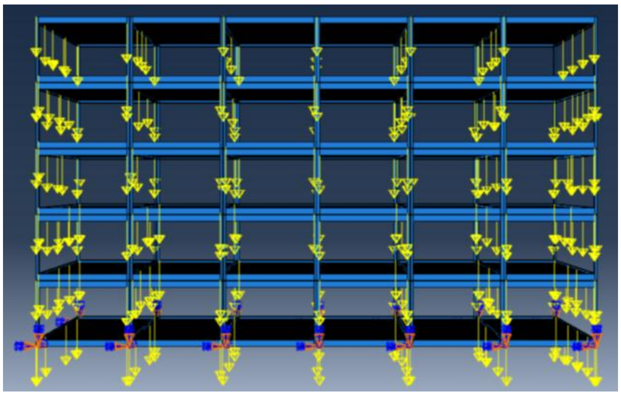
6. METHODOLOGY

Modelling a multi-storied steel framed building model in Abaqus software. Considering two module loss scenarios along with normal loading condition. Analysing the configurations as dynamic explicit models. Identifying the alternate load paths for load redistribution. Analysing the stresses, structural response curves and the time history graphs for the three different configurations. Theoretically suggesting methods to improve the collapse resistance

7. ANALYSIS OF FINITE ELEMENT MODEL

The structure was modelled as a five-storey office building assembled with steel-framed modules. Each comprised a series of identical corner-supported modules 9 m long, 3 m high and 3.6 m wide. For each module, PFC 300 parallel flange channels were chosen for all the edge beams and beams at the intermediate columns. PFC 150 was chosen for all the purlins and the spacing was 375 mm for floor purlins. SHS 100 × 100 × 5mm was used for all corner and intermediate posts. All the elements were separately meshed and assembled together. The material properties were taken as density of 7850 kg/m3, elastic modulus (E) of 206 GPa, a yield stress of 355 MPa, Poisson's ratio of 0.3 for a grade S355 steel member. Fig 6.2 shows the meshed model.

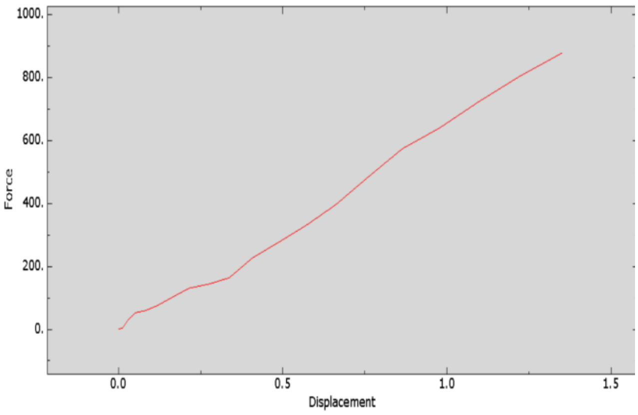
The model is modelled by stacking the modules with a gap of 25mm which are interconnected using coupling constraints. The model is loaded with a factored load of 207kN (6.4kN/m^2) on each module. The loading comprises of dead load, superimposed dead load of 1kN/m^2 and a live load of 3kN/m^2.



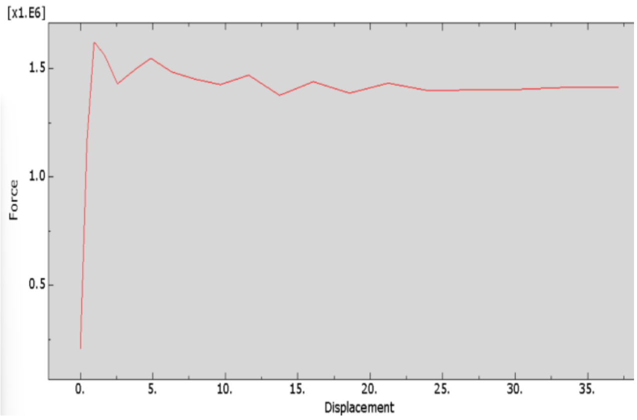
7.1 **Module loss scenarios**

Two module loss scenarios were considered. The first case considered a corner module loss where the module from the left corner of the ground floor is removed. The second case considered removal of two intermediate modules from the ground floor. The analyses of the two cases are discussed below.

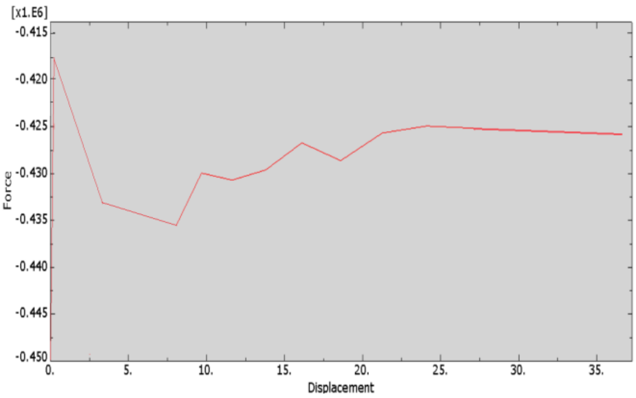
- Structural response curve



Normal loading condition

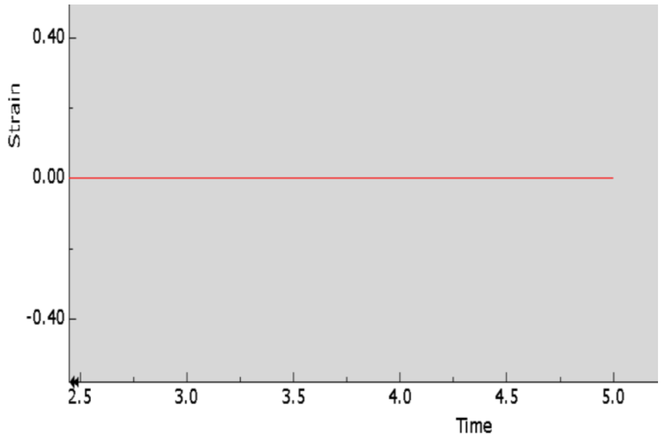


Module loss scenario 1

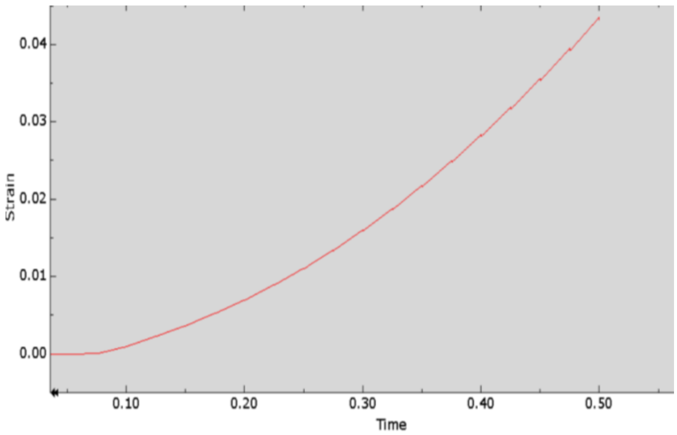


Module loss scenario 2

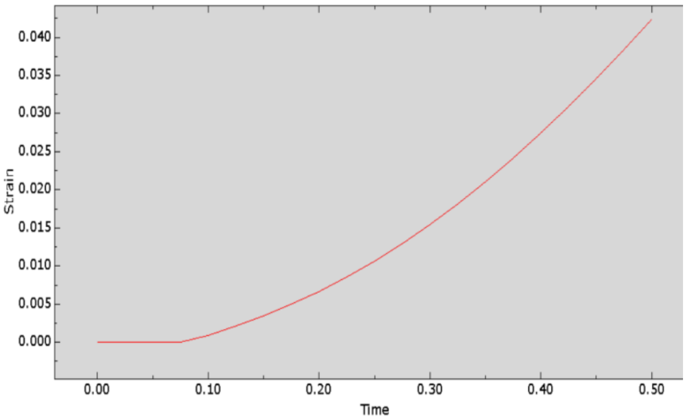
- Equivalent Plastic strain curve



Normal loading condition



Module loss scenario 1



Module loss scenario 2

8. INFERENCE

The stress distribution diagram shows that the stresses have realised the alternate load paths to redistribute. The stress reaches the maximum yield stress fastest in case of second module loss scenario than the first case. In normal loading condition, the stress is not reaching its maximum limit. Under normal loading condition, the force versus displacement relationship is almost linear. The graphs in the case of module loss scenarios are irregular because the forces redistribute and the enters into the plastic region.

Plastic strain is in zero for normal loading condition. The plastic strain increases corresponding to axial tension or compression in the uniaxial direction in case of abnormal loading conditions.

9. CONCLUSIONS

1. The analysis is carried out for normal loading condition and two module loss scenarios.
2. Analyzing the stress diagrams and structural response curves, it is found out that the loads have realized alternate paths to redistribute.
3. The condition where two modules have removed is found to reach the ultimate yield stress faster than when removing the corner module.
4. To increase the resistance of modular buildings against progressive collapse- increasing the size of the structural members, providing more intermodular connections, provide sufficient bracings etc.

10. REFERENCES

1. Luo, F. J., Bai, Y., Hou, J., & Huang, Y. (2019). "*Progressive collapse analysis and structural robustness of steel-framed modular buildings*". Engineering Failure Analysis, 104, 643–656.
2. Alembagheri, M., Sharafi, P., Hajirezaei, R., & Samali, B. (2020). Collapse capacity of modular steel buildings subject to module loss scenarios: The role of inter-module connections. *Engineering Structures*, *210*, 110373.
3. Thai, H. T., Ho, Q. V., Li, W., & Ngo, T. (2021). Progressive collapse and robustness of modular high-rise buildings. *Structure and Infrastructure Engineering*, 1-13.
4. Lacey, A. W., Chen, W., Hao, H., & Bi, K. (2019). Review of bolted inter-module connections in modular steel buildings. *Journal of Building Engineering*, *23*, 207-219.
5. Andrew W Lacey, Wensu Chen, Hong Hao and Kaiming Bi, Structural Response of Modular Buildings – An Overview, Journal of Building Engineering
6. ABAQUS. ABAQUS theory manual. I. Hibbitt, editor. Pawtucket (RI): Karlsson and Sorensen; 2017