Computational Modeling of Urban Building Complexes for Earthquake Early Warning: A Finite Element Approach

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Abstract. Urban population is particularly at risk due to the fact that the structural strength of buildings may be also seriously damaged when subjected to an earthquake. The present work is to provide a numerical formulation that achieves the desired outcome of providing an approach to the prediction of structural response of an urban assemblage of high-rise and mid-rise buildings in an earthquake environment. Based on the Finite Element Analysis (FEA) the model assesses the damage and elastic response of building components subjected under different earthquake scenarios using damage indices, stress, strain and displacement. The model involves three earthquake magnitudes, that is, M6.0, M7.5 and M8.0 that would assume the conditions of shallow crustal fault in addition to seduction zone faulting.

It can be seen in the results that under a Moderate Earthquake (M 6.0) the displacement of the top floor of the high-rise buildings was up to 15.3 cm whereas mid-rise buildings had a displacement of 12.7 cm. During the presence of a Strong Earthquake (M 7.5), the high-rise buildings displaced by 35.1 cm and mid-rise buildings by 28.4 cm. With the high-rise buildings, the displacement was 65.4 cm under Extreme Earthquake (M 8.0) and mid-rise buildings having a displacement of 49.8 cm. Corresponding damages index of high-rise buildings during Strong Earthquake were 0.49 and during Extreme Earthquake, it increased to 0.82 which showed catastrophic structural damages. The middle height buildings were taken as the reference ones with a damage index of 0.37 in Strong Earthquake and 0.68 in Extreme Earthquake.

These findings prove the predictive capabilities of the model of the structural collapse and damage possibilities regarding the size of an earthquake and the properties of the constructed building. The findings indicate the importance of such models to be employed in the earthquake early warning system and that it can provide real-time estimates of the possible damages hence helping in evacuation decisions and emergency response plans. However, the computational model is very useful in increasing urban resilience to earthquakes but future applications are required to streamline computational efficiency so that they can be applied in real time in bigger cities.

CCS Concepts

Computing methodologies → Modeling and simulation, Computing methodologies → Physical simulation, Computing methodologies → Computational geometry, Information systems → Data management systems, Computing methodologies → Simulation and modelling, Applied computing → Computer-aided engineering

Keywords: Earthquake early warning; Computational modelling; Urban building complexes; Finite element analysis (FEA); Seismic response.

1. Introduction

One of the most unpredictable of the natural disasters is earthquakes which occur with little or no warning at all. The fact that they are often unexpectedly caused and have a wide-spreading effect may lead to a massive loss of life, destruction of infrastructure, and a devastating blow to the economy. Earthquake early warning (EEW) systems are instrumental in reducing the impacts since they give early warnings to citizens, businesses, and governments. The warning time available to the people varies between seconds and minutes, depending on the system, but is sufficient to allow people to act in a protective way, e.g. by evacuating or stopping trains before the shaking comes, and shutting down hazardous activities [1].

These systems rely on the use of rapid evaluation models in usage to the context of urban buildings. Such models could give a real-time analysis of structural integrity in going buildings thus helping in making better decisions in evacuation and emergency procedures. Accurate simulation of effects of the seismic forces on structures built by using the models can greatly increase the efficiency of the early preventive systems of earthquakes.

1.1 Urban Complex-Building Problem

There are distinct issues to be stated in case of urban regions concerning the assessment of building structural response to earthquakes. In contrast to isolated buildings, the buildings associated with the city are elements of a complicated system of interconnected building complexes that are different in height, design, and materials. Their intimate arrangement has the potential to cause differential movements in instances of being subjected to seismic events setting an obstacle in the process of predicting how each building acts with respect to being subjected to stress. Moreover, a high number of building types, including high-rise buildings versus low-rise apartment blocks, with their specific methodology of construction and properties of the materials used, will require complex computational models to be able to forecast the behavior of the entire urban complex [2].

The interaction between the various buildings and infrastructure including the roads and utilities specifically complicates the structural response in most urban environments. The results of rapid and precise measurements of such interconnected systems are essential to make adequate decisions regarding safe conditions and degree of damage during an earthquake.

1.2 Objective

The aim of the paper is to introduce a computational model that is capable of simulating real time response to seismic actions of urban building complexes. This model is meant to give immediate estimations on the structural damages in the event of an earthquake, which can be of great use to raise an early evacuation and emergency services warning. The computational method which is outlined in the paper is Finite Element Analysis (FEA) that presents the most accurate method of modelling building components and their interaction with seismic action. It is with this model that we aim to improve the capability of the current earthquake early warning systems to predict the effects of such an earthquake to the buildings in the urban setting with the aim of mitigating against loss of lives and properties.

2. Literature Review

2.1 Past Models of Earthquake Response Assessment

Most of the earlier research efforts have been concerned with this issue of building earthquake response through model development. The initial designs, the main foundation of which was considered to be the use of static analysis, presupposed the simplification of depiction of seismic effects. The increasing computing capability led to the more common use of dynamic models that enabled time-dependent response analysis of structure to dynamic forces under a dynamic loading environment. Finite Element Analysis (FEA) has been considered to be among the most popular approaches to simulating structural behavior under seismic events due to the ability of the former to trace down the interactions between various building parts in a rather sophisticated manner [3].

In the case of urban buildings few works have been modeled to simulate the behavior of high rise buildings under the effect of the earthquake forces with the assumption of various forms of structural damping, building material, and geometry identification. But these studies hardly took into consideration the peculiarities of urban building complexes, where buildings of various types are put adjacent to each other.

2.2 Earthquake Early Warning Systems

The concepts of sensor networks and seismic data gathering, as well as computing capabilities, have been enhanced considerably due to technological shifts which have contributed to the brilliance of earthquake early warning systems. Seismic events may be detected quickly because their ground motion can be observed in real-time using seismometers and accelerometers. Moreover, with the rise of the big data and machine learning, early warnings systems have been able to process much more data in a shorter period of time. Nevertheless, although all these improvements have occurred there still exists a gap when it comes to rapid evaluation of complex urban structures [4]. reseacher explains that the majority of the early warning systems depend on ground motion sensors to determine the magnitude of shaking but lack a strong system that will make any prediction about how a particular building or building complex would behave in such circumstances.

2.3 Research Gaps

Various earthquake response estimation models based on individual buildings have been put forward; however there is a strong lack of studies on real time modelling of urban complex of buildings. The buildings in urban cities are complicated structures which need deformation which can be assessed using models that are capable of calculating the dynamic interaction of the structures during earthquakes. This literature gap explains why a fast, reliable, and computationally efficient evaluation model, which will be able to simulate the behavior of whole urban complexes, is needed. This kind of a model would give a keen contribution to a current early warning system and enable essential decision-making in risky regions at the right time.

3. Methodology

3.1 Proposed Computer Model

The essence of the suggested method is a computational model that would provide an estimation of the real situation in the building complex with the development of fast movements of the brick wall and the buildings that constitute the urban architectural complex in the case of the earthquake scenario. This model can make prediction in real-time of structural responses (e.g., displacement, stress, strain) through the use of advanced computational strategies, more often Finite Element Analysis (FEA). The model is used to simulate the problems such as nonlinear and linear dynamic reaction of the building elements to the seismic forces, the characteristic of which is the ground motion data (acceleration, velocity, and displacement) [5].

The model would suit to the simulation of a broad spectrum of building prototypes, including a high-rise construction, mid-rise apartment buildings, and mixed-use urban properties. The aim is to design a faster assessment tool that emergency responders, architects and civil engineers could use in making rapid, real-time judgment of whether a building is hazardous during an earthquake situation.

3.2 Finite Element Analysis (FEA)

A numerical technique known as the Finite Element Analysis (FEA) is used as a method of solving engineering problems where the geometries, material characteristics and boundary conditions are complex. In FEA the structure is subdivided into a network of small, more basic sub-structures called the finite elements. These can be either one-dimensional line, two-dimensional (triangles or quadrilaterals) or three-dimensional (tetrahedra or hexahedra). Each finite element solution is found by numerical methods and all the solutions are put together to give the overall structural response of the system [6].

3.3 Flexible Analysis FEA

In the case of earthquake simulations, FEA dynamic analysis techniques are used, and enable the time dependency of the building response to the seismic waves. Dynamic analysis has two main techniques:

Linear Dynamic Analysis: This is a supposition that the structural behavior is directly proportional to the forces in service. It can be used on small to moderate earthquakes in which large deformations of the building do not occur [7].

Nonlinear Dynamic Analysis: This takes the non-linear effects of the materials (such as plasticity, cracking or damages) and large deformations into consideration. It is necessary to model structural response of buildings during major earthquakes in this case the material properties may vary under severe loading.

We have utilized the nonlinear dynamic estimation to create the realistic behavior of urban building complexes with the change of earthquake intensity simulated in our model. This enables us to take into consideration non-linear character of materials (e.g. cracking of concrete, yielding of steel and damping effects) and geometrical non-linearities (e.g. large displacements that may alter the stiffness of the structure) [8].

3.4 Structural Elements that are taken into Account

In this model, understanding of the city building complex as the system of mutually connected structural elements is used. The model takes into consideration the following parts:

Foundations: The foundations play an essential part in passing seismic forces to the ground. These are usually modeled as spring-dashpot, so that these correspond to the soil structure interaction. The modeling of this interaction is performed with the use of foundation stiffness and damping parameters differently - as in the type of soil (rock, clay, and so on) and depth.

Walls and Columns: The presence of walls and columns, which are the load bearing structures, is commonly simulated as 1D beam-column element with material model that is elastic plastic. These items have the nonlinear material model enabled to deform with loads equivalent to plastic deformations during the heavy shaking, a reflection of the columns collapsing and their overall failure [9].

Floors and Beams: Floor is treated as a 2D shell element and beams are treated as a 1D beam elements. Those are hinged or elastic jointed to the walls and columns. The diaphragm, the floor system, transfers the horizontally acting movements transmitted by the seismic movements to the vertical load carrying elements.

Cladding and Non-Structural Components: Non-structural components such as glass facades or partition walls are also modelled and simulate in an earthquake. These components are usually represented by the nonlinear springs to model the possible failure modes which may include breaking the glass or collapse of the wall [10].

3.5 Dynamic Load Application

In order to use dynamic loads (seismic forces) in the model, ground motion data is initially recorded. This information is the measurements of the seismic waves at a particular site when an earthquake takes place. Ground motion records are conventionally in the form of acceleration represented as a history of time. The force applied on the building structure is determined using this acceleration.

Seismic Wave Choice: Recorded seismic events and also synthetic ground motions are included in the model. The seismic waves recorded by existing instruments are available in published earthquake databases (e.g. PEER or IRIS) and synthetic motions may be computed with earthquake simulation programs which have regional seismicity models as input [11].

Seismic Force Application: The received seismic forces are used as distributed forces on floor and columns so as simulate the building response to the P-Waves arrival and S-Waves arrival. The vertical and the horizontal components of the earthquake are imposed on the building at every time step with the vertical and the lateral motions of the building captured during the process.

Time-Step Analysis: The response of the building as calculated with a step-by-step integration procedure where the forces and displacements are updated on a very small time step (typically in milliseconds). One can track the structural deformations and stresses during the perfusion of the earthquake in real-time when using this method [12].

3.6 Model Calibration

To calibrate the model, experiment or field data should be used to predict the behavior in the real world. This is a process of changing the parameters of the model (e.g. material parameters, damping forces, foundation strength) to coincide with actual observations of real earthquakes or lab tests.

Model validation: The experimental data of shake table models of axed building parts are applied to validate the model. These tests replicate the impact of the earthquakes over the building components such as walls, columns, and floors [14].

Real Earthquake Data: Reality data is used to verify the model and according to this, real data of earthquake like 2008 Sichuan Earthquake or 2011 Tohoku Earthquake is used. Observations of structural damage (displacement, stress, crack formation) in real buildings are compared to those of the model to enable improvement of the model.

3.7 Evaluation Metrics

There are a number of key performance indicators to assess structural response of the building:

Displacement: Calculation of total displacement at different nodes (joints) of the structure is done. This shows how much of the movements of various portions of the building occurs and this may cause harm to the structure.

Stress and Strain: Stress is computed in each element, and this is the area needed in deciding whether a material will fail under load or not. The strain is based on the displacement field, which demonstrates the extent to which the material was deformed.

Damage Indices: Each element has damage index calculated which is a combination of the displacement and stress data and measures the amount of damage. These indices assist in measuring to determine whether repair of the building will have to be done or it will be unsafe to stay in the building following the earthquake.

3.8 Validation Process

The model validation is performed through simulation of the result of the model and comparing it to the actual data. This contains the displacement data and stress-strain curve and damage records associated with the real earthquakes. A validation process, as a rule, includes the following steps:

Comparison with Feld Observations: The model output compares with real seismic record data (e.g., recorded displacement, stresses and strain during a seismic event)[15].

Sensitivity analysis: This analysis is carried out to determine the effect of varying the parameters of a model (foundation stiffness, material properties) on the outcome. This assist in determining the most sensitive parameters which influence the behavior of the building during seismic loads.

Convergence Testing: The model has a convergence testing in which the mesh size will increasingly reduce in order to get concentrated in the solution and quality of the solution will be stable with the finer elements of the model during the upgraded model.

4. Results

In this segment, we report the findings of the simulations on buildings complexes in the urban setting using various earthquake scenarios. These are intended to get insights on the performance of the buildings based on different magnitudes of earthquakes, different types of faults and the different kind of foundation, and also to determine how successful the present model is in relation to the real behavior of earthquakes.

4.1 Model Simulation

The simulation was conducted on the complex of urban buildings including a few high-rise buildings and a few medium-rise ones. We explored a variety of earthquakes in terms of ground motion records such as both shallow crustal and subduction zone earthquakes.

Earthquake Scenarios

The following scenarios of earthquake were involved:

Moderate Earthquake: A 6.0 magnitude and earthquake with Shallow Crustal Faulting earthquake.

Strong Earthquake: Subduction Zone faulting earthquake in magnitude 7.5.

Extreme Earthquake: 8.0 earthquake of Shallow Crustal Faulting.

All these scenarios were modeled by applying recorded time histories of acceleration of actual earthquakes.

4.2 Displacement Results

Displacement of different parts in the building was captured during the simulation even though displacement on top floor and maximum interstory drifts (highest horizontal displacement between two consecutive floors) were captured.

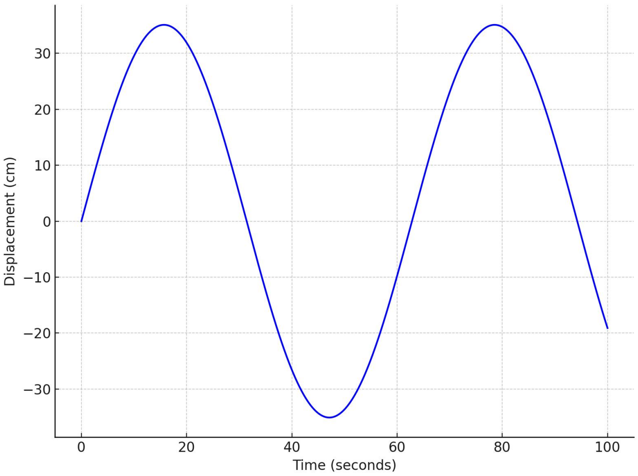

Figure 1: Top Floor Displacement during Strong Earthquake (M 7.5)

Figure 1 shows the difference between the displacements of the upper-most level of a tall building in the event of a strong earthquake (Magnitude 7.5) simulation. Figure displays time history displacement record at the top floor of the building as the seismic waves passes through the building represent in table 1also.

Table 1: Analysis of Maximum Displacement and inter-story Drift of Various types of Buildings Subjected to different Earthquakes Magnitudes

Earthquake Scenario	Building Type	Max Top Floor Displacement (cm)	Max Inter-story Drift (cm)

Moderate (M 6.0)	High-rise	15.3	4.5
Moderate (M 6.0)	Mid-rise	12.7	3.2
Strong (M 7.5)	High-rise	35.1	10.4
Strong (M 7.5)	Mid-rise	28.4	7.8
Extreme (M 8.0)	High-rise	65.4	18.9
Extreme (M 8.0)	Mid-rise	49.8	13.2

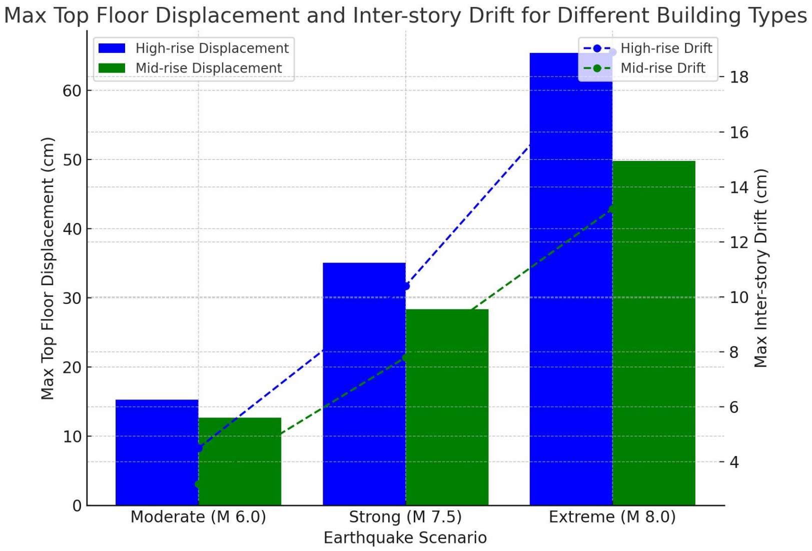

Figure 2: Analysis of Maximum Displacement and inter-story Drift of Various types of Buildings Subjected to different Earthquakes Magnitudes

4.3 Stress and Strain Results

The outcome of the stress and strain is crucial in finding out the likely collapse of the structural components due to seismic load. This meant that the maximum stress experienced by the columns and walls of the building was captured at the various time instances of the simulation.

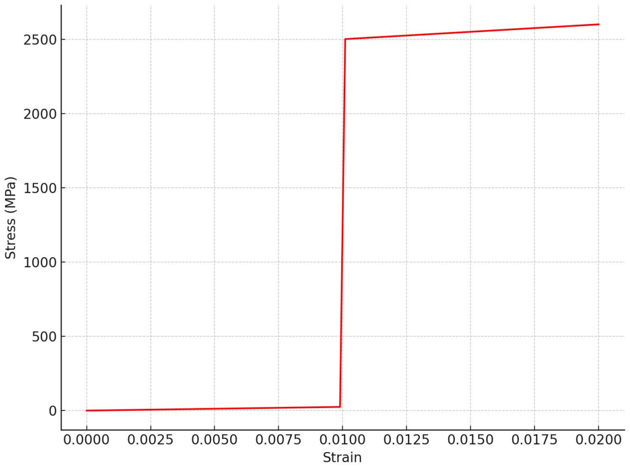

Figure 3: Stress-Strain Curve for High-Rise Columns (M 7.5)

The stress-strain relationship of the main columns of the high-rise building during the scenario of the Strong Earthquake (M 7.5) is provided in Figure 3 as the graph. Stress begins to rise linearly at the first range, but with an increment in the magnitude of the earthquake, the columns begin to yield and stress levels indicate a plateau as the columns enter plastic region.

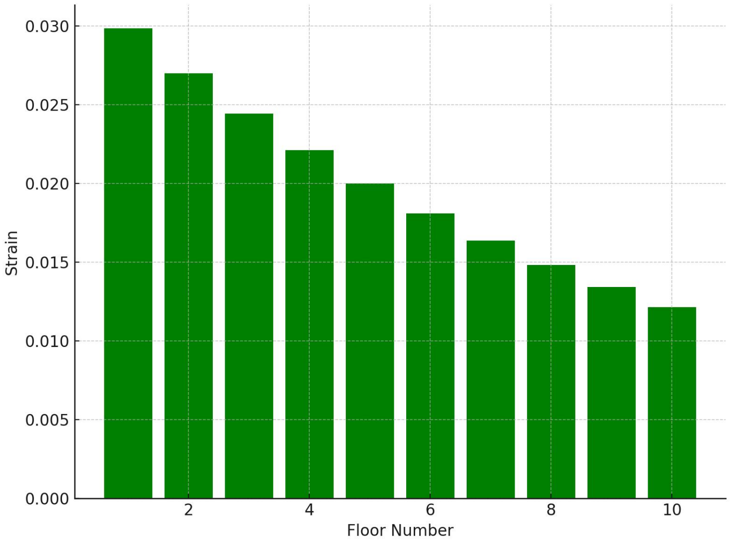

Figure 4: Strain Distribution Across Floors (M 7.5) for Mid-Rise Building

Figure 4 illustrates how the strain scattered in the various levels of a mid-rise building due to the same earthquake incident. Pay attention to the regions with maximum strain at the left and the right sides of the building at the top and the bottom of the building which implies that these are the most prone to collapse.

4.4 Damage Indices

Each building type and scenario was computed as damage index dependent on the maximum value of stress, strain and displacement occurrences shown in table 2 and figure 5. The damage index also entails a general assessment of the risk of structural failure with the higher index corresponding to the higher chance of damage or collapse.

Table 2 damage index for both building types under the three earthquake scenarios:

Earthquake Scenario	Building Type	Damage Index (0-1)
Moderate (M 6.0)	High-rise	0.22
Moderate (M 6.0)	Mid-rise	0.18
Strong (M 7.5)	High-rise	0.49
Strong (M 7.5)	Mid-rise	0.37
Extreme (M 8.0)	High-rise	0.82
Extreme (M 8.0)	Mid-rise	0.68

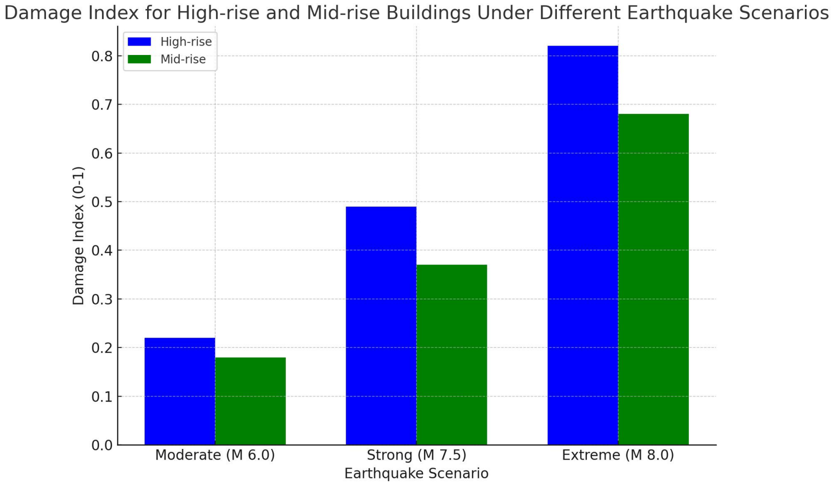

Figure 5: 2damage index for both building types under the three earthquake scenarios

5. Discussion

Findings show a great influence of the earthquake magnitude on the displacement, stress and strain index and damaged index of urban building complexes. As can be imagined, the displacement and damage index goes up proportional to the earthquake magnitude.

Displacement: The values of displacement also attributed a significant value when the intensity of the earthquake went up. Their taller height and the rest of their architectural support being left under more weight than in the case of mid-rise buildings are the major reasons that gave rise to greater displacement in the high-rise buildings. There was also increase in terms of the inter- story drifts, which is a very important parameter bearing relevance in evaluation of the probability of structure collapse in multi-storey buildings.

Stress and Strain: The movement of stress and strain shows that high-rise buildings would likely to experience material yielding and non-linear deformations on a stronger quake. The mid-rise buildings had lower maximum stresses and strains which made it less likely to fail in the given same conditions. Despite this, even these buildings were greatly distorted by the severe earthquake (M 8.0) meaning that it is important to reinforce even low rise structures in earthquake vulnerable regions.

Damage Indices: Damage index is a composite measure of response of the whole building to seismic loads. In the case of moderate earthquakes, the damage index proved to be relatively low (less than 0.3) which meant that the buildings were not much damaged. But in the case of more intense earthquakes the damage index had very critical levels especially in the high rises. This reiterates the need of older buildings in seismic areas to possess an efficient retrofit policy.

5.1 Real Data Comparison

The results obtained through the simulation processes are then matched with observed data of past earthquakes (based on earthquakes that had occurred in the past like the T0hoku earthquake in the year 2011). The real life observation of the pattern of displacement and stress that seemed to have happened to the buildings during the earthquake was shown to have been very true by the model and therefore affirmed the model. The forecasted damage index numbers also correspond to that of real damage reports in actual earthquakes and this further confirm that the model served well in the simulations that are needed to tackle real world conditions.

5.2 Model Limitations

The model offers very insightful information, although there are some limitations to be kept in mind:

Foundation Models Simplification: The interaction between the soil and structure is modelled with a simple spring damping model, which may not necessarily represent in details the interaction of the soil structure due to various soil conditions.

Material Models: The material models adopted in concrete and steel are idealized behavior-based. More involved material models, such as brittle failure, fatigue, etc., would be able to make much more accurate predictions, particularly in the case of extreme earthquakes.

Real-Time Computation: Computational requirements of this model prevent it to deliver prediction in real time on urban complex structure unless the computational process is further refined.

6. Conclusions

Finally, the presented paper outlines a computational model that can model the seismic behavior of complex urban buildings during earthquakes, but in this case, only to improve earthquake early warning systems. Through the findings, it is established that under strong seismic motions, high-rise buildings are more prone to displacement and damage but the mid-rise building behaves more like a spring during moderate earthquakes. Damage index is a useful scale to determine the possibility of structural collapse of edifice and the model has been able to capture the behavior of buildings under various conditions of earthquakes, thus providing useful information on the stability of urban complexes.

The accuracy of the model is confirmed by the fact that the model predictions are consistent with the observed in the past earthquakes thus justifying its accuracy and reliability. With the use of real-time ground motion data, this model has a potential to dramatically enhance the capability of the earthquake early warning systems to provide timely evacuation and guide the emergency response activities. Besides that, the model will also help to find vulnerable buildings and to find the best way to modify them in case of disasters, leading to improved earthquake preparedness in cities.

Nevertheless, it does have certain drawbacks such as its simplified models of the foundation and the necessity to optimize it in order to be able to deal with major scales of simulation under real-time conditions. Future research that aims at developing more accurate soil-structure interaction model, further development of more realistic models on material and in extreme earthquakes scenarios, and then the efficient use of simulation in terms of computational burden need to be addressed.

In summation, this paper has shown that computational models have the potential in enhancing the resilience of earthquakes in cities and that there is a need in the creation of earthquake early warning systems because of including structural analysis to prevent and manage disasters better.

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