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Robustness analysis of steel structures with various lateral load resisting systems under the seismic progressive collapse

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A B S T R A C T

Robustness is called to non-sensitivity of a structure to local damage. In the literature of Civil Engineering, the sensitivity of structures to the local damage which can cause a progressive collapse is called Robustness Index. After 9/11, progressive collapse drew the attention of researchers and since that time, increasing the Robustness Index in a structure has been considered as one of the factors in strengthening the structure against progressive collapse. The aim of this study is assessing the Robustness Indices of steel structures having various lateral load resisting systems. So, 8-story, 4-story and 15-story structures with Moment Frames, Concentrically Braced Frames and Eccentrically Braced Frames were modeled and assessed under Robustness analysis. For a progressive collapse analysis, the Alternative Load Path method was used and after emerging local damage, the potential of progressive collapse was assessed using the Robustness Index. First, Robustness analysis was carried out on the basis of Robustness Index assessment using Stiffness and Base Shear methods. Subsequently, it continued by introducing a simple method based on Energy. The results show that despite their simplicity, the methods which are based on Stiffness and the Base Shear, have lots of disadvantages. But, the Energy method has better capabilities for understanding the behavior of structure under seismic loads in progressive collapse scenario. Furthermore, structures which have bracing had a better reaction in progressive collapse scenario.

1. Introduction

The collapse of one or some structural members under unexpected loads, which eventually causes collapse of whole the structure, is called progressive collapse [7]. In fact, if the structure cannot stand the extra load caused by omitting a column or it cannot find new ways for transferring the mentioned load, the damage will spread out in the structure and lead to damage in the structure itself. In other words, if the structure cannot neutralize the kinetic energy produced by local damage, omitting important members and loading, through damping and plastic or elastic strain energy, the structure collapses. For the first time, after collapsing a part of Ronan Point building in London in 1986, this issue drew the attention of engineering societies and after 9/11 attacks in 2001, several standardization committees started to work on methods for promoting the standards of designing against progressive collapse [4].

Progressive collapse can be caused by explosions, car accidents, fire, etc. or natural disasters like earthquakes. Earthquakes can produce considerable forces and tensions in structures. The effect of this load can overload structural members up to the extent that they lose their strength and the structure may lose more members [17]. Observing the damage of previous earthquakes, shows that seismic loading can cause damage to structural elements and subsequently, early failure of structural elements can cause secondary

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damage to other members. Starossek [11] categorized the progressive collapse into six types. This classification was according to the behavior of structure and its damage expansion type without considering early causes of damage. 1-Pancake collapse: in this sort of failure, elements and rearrangements of forces caused by damage have the same direction, similar to Word Trade Centers collapse. 2-Zipper collapse: in this type of collapse elements and rearrangements of forces are perpendicular, like the collapse of cable bridges. 3-Domino collapse: this type of collapse is caused by members overturning or colliding structures or members with adjacent structures or members. 4-Cross sectional collapse: it happens due to material yielding and rearrangement of forces in adjacent members. 5-Damages due to instability: this sort of failure happens due to destroying constraints and so, losing structural stability in structures. In a static state, if the element is under pressure, the happened instability is called buckling. 6-Combined failure: most of happened collapses cannot be placed in one of the mentioned groups and they gather characteristics of some of failure types. This sort of failure is called combined failure.

In contemporary designing codes, structural designs are acceptable just for loads which may affect a building during its usage period. And structures will not be designed for unexpected occurrences that may cause enormous damage. Most of common designing codes just have general advice for adjusting the effect of progressive collapse for structures, in which, applied loads are bigger that design loads. In the USA, General Service Association [2] and Department of Defense [20] presented extensive information and instructions which contain solutions for strengthening buildings against progressive collapse. Among various methods for designing buildings against progressive collapse, designing codes usually propose Alternative Load Path method. In the mentioned method, the building will be designed on the basis that if one of members collapses, alternative paths for load distribution are accessible and general collapse will not happen for the building. Actually, in this method, the damaged member will be omitted from the structure and this issue will be assessed that if other elements are capable enough for resisting against the extra loads caused by this elimination. In order to investigating the progressive collapse phenomenon in structures, codes have proposed linear static analysis, linear dynamic analysis, nonlinear static analysis and nonlinear dynamic analysis [22].

In Kapil Khandelwal & Sherif El-Tawil [5] research, they investigated the progressive collapse in braced steel frames, that are designed according to seismic criteria, using APM method. H.·Tavakoli and F.·Kiakojouri [14,16] investigated the progressive collapse of steel frames subject to explosion loads according to AMP method. They assessed various column elimination scenarios. H.·Tavakoli and A. Rashidi [15] investigated the progressive collapse in Moment Frames resisting systems. The results of their study showed that the structure has higher strength in eliminating the middle column rather than eliminating a corner column. Tavakoli et al. [18] investigated the potential of progressive collapse in concrete buildings under gravitational and lateral loads. The results show that concrete buildings under gravitational loads have acceptable strength against progressive collapse. Tavakoli et al. [17] investigated the potential of progressive collapse in concrete and steel structures using seismic requirements. The results showed that local damage in the lower stories does not cause progressive collapse. Liu and Pirmoz [9] worked on a method that had been according to energy for Pushdown analysis in assessing the potential of progressive collapse in steel structures. They believed that, assessing the potential of progressive collapse using Pushdown analysis method, according to energy, has more realistic capability, speed and results. Khuyen and Lwasaki [6] presented an approximate method for determining the Dynamic Magnification Factor in the alternative path method in steel bridges subject to progressive collapse.

Wibowo & Lau [21] presented a short review of progressive collapse phenomenon. They argued methods and requirements of several standards in preventing progressive collapse. It was found that, seismic progressive collapse of structures can be analyzed if the present methods are modified. Jinkoo Kim & Taewan Kim [8] investigated the strength capacity against progressive collapse in steel frames. The result of their study was that Nonlinear Dynamic Analysis is an exact means for assessing the potential of progressive collapse in buildings. Szyniszewski and Krauthammer [13] investigated the progressive collapse according to energy flow. In this method, the structure will remain safe if the kinetic energy caused by a sudden omitting of one column is neutralized with elastic strain energy and damping. Otherwise, it will experience damage.

Victoria Maria Janssens [3] in her investigations, in modeling the progressive collapse scenario, found that the Linear Static Analysis is somehow conservative in comparison to Nonlinear Analysis.

Robustness has been defined as insensitivity of a structure to local damage. In other words, Robustness of structure is the safety of structure after local damage. Robustness can be investigated using three different methods; Non-probabilistic methods, Probabilistic methods and Risk-based approaches. Multiple equations have been proposed for investigating Robustness Index, among which, we can mention Robustness Index assessment base on Stiffness, damage method, Energy method and Base Shear method. In this study, just Non-probabilistic methods for investigating Robustness Index have been taken into account.

The simplest way for estimating Robustness is utilizing Stiffness method which can be calculated using the following equation.

$$R_s = \min_j \frac{\det k_j}{\det k_0} \tag{1}$$

where R_s is Robustness based on stiffness, k_j is the stiffness of damaged structure and k_0 is the stiffness of the intact structure. Another method for evaluating the Robustness Index of the structures is applying Energy method. According to this method the Robustness Index is calculated using the following equation:

$$R_e = 1 - \max_j \frac{E_{r,j}}{E_{f,k}} \tag{2}$$

where, R_e is the estimated Robustness Index based on energy, $E_{r,j}$ is the released energy during local damage of the structural member j that damages the member k, and $E_{f,k}$ is the needed energy for destroying the damaged element k [10].