SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

SEISMIC PROGRESSIVE COLLAPSE ASSESSMENT OF RC MOMENT RESISTING BUILDINGS WITH ECCENTRICITY IN PLAN

Abdolreza S. MOGHADAM [1] and Somayyeh KARIMIAN [1]

ABSTRACT

Margin of safety against potential of progressive collapse is an important property of a structural system. Often eccentricity in plan of a building causes concentration of damage, thus adversely affects progressive collapse safety margin of that building. In this paper seismic progressive collapse assessment of reinforced concrete moment resisting buildings with eccentricity in plan are studied. The building models are symmetric and asymmetric six-story reinforced concrete ordinary moment resisting frame buildings subjected to earthquake ground motions. The asymmetric buildings have 5%, 15% and 25% mass eccentricity. The distribution of damage and spread of collapse is investigated using nonlinear time history analyses. It is shown that increase in level of asymmetry in buildings causes an increase in potential of progressive collapse at both flexible and stiff edges of buildings. Spread of the collapse is independent of the earthquake records and is horizontal through the stories not vertical through the height of the buildings. According to the results, probability of collapse initiation from the columns increases when mass eccentricity increases. Generally, collapse in asymmetric buildings initiates mainly on the flexible edge of the building. It is also demonstrated that "drift" as a more easily available global response parameter of frame, is a good measure for a much difficult to calculate local response parameter of "number of post collapse plastic hinges".

INTRODUCTION

Progressive collapse mechanism in a structure means the collapse of a major/big portion or entire of the building which is initiated by the propagation of local damages in such a way that the structural system cannot bear the main structural loads. In this mechanism, the final damage state is much more than the initial local damages (Ellingwood 2006).Vehicular collision, accidental overload, aircraft impact, design/construction error, fire, gas explosions, bomb explosions, hazardous materials, etc are as a number of abnormal loads which can potentially be the trigger of progressive collapse in the various buildings (Somes 1973; Burnett 1975a).

The relationship between earthquake-resistant reinforced concrete structures and progressive collapse mechanism were studied by Tsai and Lin (2008) according to GSA guidelines. Linear static, nonlinear static and nonlinear dynamic analyses were performed in the structures subjected to the columns removal. Results showed that because of the different collapse resistances, GSA criteria should be different for the two different nonlinear analyses and a dynamic amplification factor (DAF) of 2 causes the nonlinear static method to be conservative. Also it is required to consider DAF in the inelastic dynamic effects in GSA linear procedure. Nonlinear static capacity curve showed that it is possible to predict DAF and progressive collapse resistance in the column-removed RC buildings (Tsai and Lin 2008).

[1] International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
moghadam@iiees.ac.ir

Progressive collapse mechanism in symmetric and asymmetric buildings was evaluated as a result of columns removal through designing 30-story regular and irregular structural models once with braced cores and once more with reinforced concrete cores. The results of analyzing the irregular structural models have shown that variation of the progressive collapse resisting capacities, were based on the location of removed columns. Progressive collapse potential of the irregular structure was increased, when the location of the removed column was determined in the tilted side of the building. The plastic hinges formed in the removed column bays and adjacent bays showed that other elements in the structural system were involved in resisting progressive collapse and when a structural member was removed, other elements contributed to resist against the progressive collapse. So, progressive collapse potentials of the asymmetric buildings were not very large in comparison with those of the corresponding symmetric buildings (Kim and Hong 2011).

Although there are many cases of the collapsed buildings in past earthquake events, usually the spread of collapse is not considered explicitly in seismic design or evaluation of the buildings. In this research the spread of collapse in the building subjected to the earthquake records is studied by continuing nonlinear time history analyses even if some elements pass their collapse limit state.

Past earthquakes have shown that torsion in asymmetric plan buildings usually causes concentration of damage in one side of those buildings. Therefore it is expected that asymmetry in a building increases the progressive collapse potential of the building.

THE REFERENCE BUILDING

The basic model is a regular 6-story reinforced concrete ordinary moment resisting frame building. This is a 3-bay by 3-bay building that each bay has a span of 5m center to center. The story height of all stories is 3.5m. The design dead load is 5.3 KN/m^2 and the design live load is 1.96 KN/m^2. The design base shear factor of the building is 0.2159. Building is designed as ordinary moment resisting frame system based on ACI (2005).

The asymmetric building models are derived from the basic model by changing their mass distribution. The mass distribution is determined to produce equal one way mass eccentricity in all floors in the x-direction. A total of four building models with eccentricities equal to 0, 5, 15 and 25 percent are considered in this study. In this study, the calibrated beam-column element model which is led to the global collapse of RC frame buildings is the one developed by Ibarra, Medina and Krawinkler (2005).

The nonlinear dynamic time history analyses are performed here using OPENSEES (Version 2.2.2) software, employing twenty two, 2-component ground motion records according to the FEMA P695, Table A-4C. Each record is normalized to the different PGA levels of 1g to 3g. These PGA levels are used to exert the intensive effect of the earthquake intensity on the structure elements, causing the collapse of the beams and columns one after another and consequently, the collapse probability increases in the whole structure FEMA P695 (2009).

THE COLLAPSE PROPAGATION

To evaluate the process of collapse propagation, first, symmetric and asymmetric buildings are analyzed due to the earthquake records, and then the sequence of collapsed elements are investigated one after another to evaluate the progressive collapse distributions. In other words, we keep tracking of the collapse scenarios in beam and column elements of the buildings. In this way, the critical beam and column elements and significant collapse distributions are identified. Results demonstrate that the majority of critical elements, and subsequently the spread of the collapse are the same per each record and mass eccentricity levels. For example, Figures 1 demonstrate the collapse propagation and sequence of the collapsed hinges which are formed in the beam and column elements of the regular and buildings for the earthquake record #752. The first critical elements hinges indicate that the critical hinges and their subsequent critical members are repeated in symmetric and asymmetric buildings.

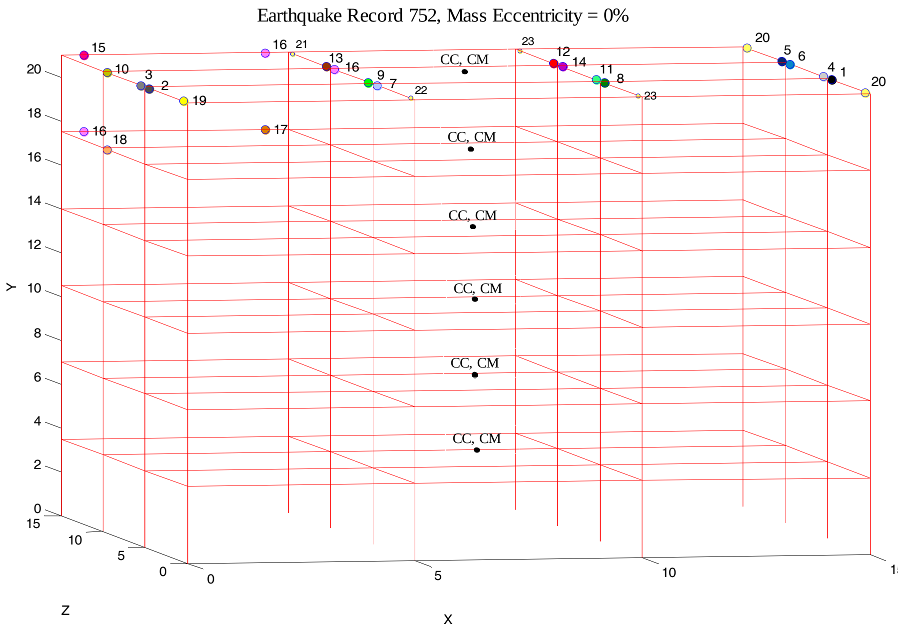

Figure 1. Collapse distribution in a regular building in presence of the ground motion record #752

In building with mass asymmetry of 25%, under some earthquake records, collapse concentrates more in the flexible areas of some floors. In other words, adversely of other types of the symmetric and asymmetric buildings which collapse distribution ends up completely in each floor and then transfer to the other floor, collapse dose not propagate totally in floors one after another, in presence of some records. Figure 2 shows collapse propagation in an asymmetric building with mass asymmetry of 25% in presence of the earthquake record 68.

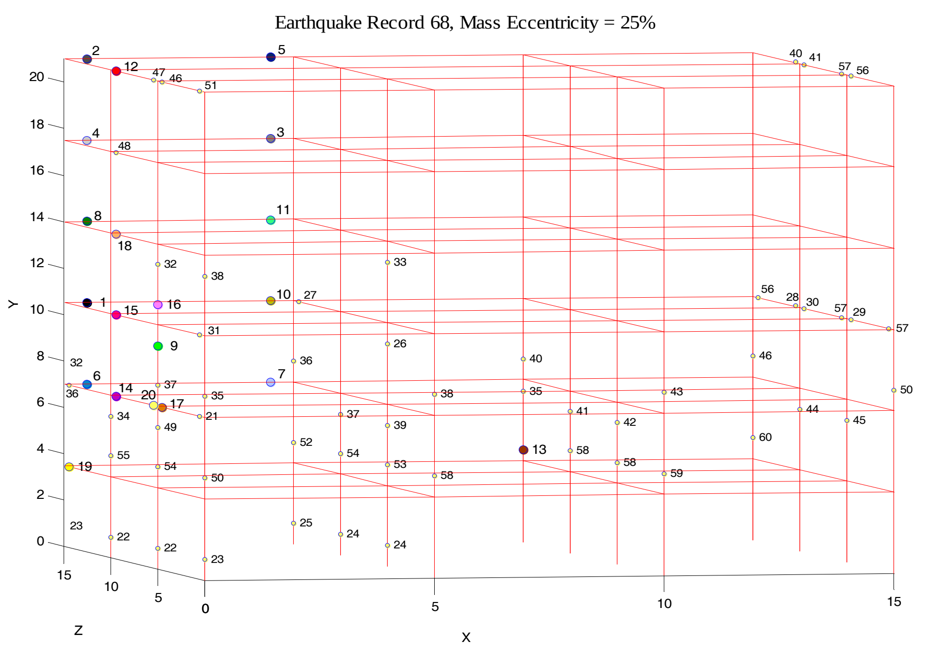

Figure **2.** Collapse distribution in an irregular building with mass asymmetry of 25% in presence of the ground motion record #68

For most of the earthquake records, failure is propagated from the left side to the right side of the building. The same process is followed for the other ground motion records and critical hinges are recognized and the sequence of the collapsed hinges is determined for the symmetric and asymmetric buildings. Results indicate that the critical collapsed hinges are fixed, almost independent of the ground motion records. Such an independency is also held for the collapse propagation. In other words, the first critical collapsed hinges and the subsequent critical members are the same in a large number of NLTHA and follow special patterns which are a function of the mass eccentricity levels. Such an outcome sounds that it is possible to predict progressive collapse scenarios and collapse propagation of the similar symmetric and asymmetric buildings.

In a large amount of the results, the spread of collapse in buildings is horizontal through the stories but not vertical through the height of the buildings, except in buildings with mass eccentricity of 25 percent, which collapse distributes vertically in some earthquake records. In other words, the collapse is propagated first through the stories. Then the distribution of the collapse will transfer to other stories. Columns contribute in the collapse process in the final steps of collapse propagation.

Since story drifts are among acceptance criteria in various codes and guidelines, one aim of this study is to achieve acceptable and useful relations between story drifts by comparing story drifts in mass centers, stiff and flexible edges of the symmetric and asymmetric buildings, to predict story drifts behavior of the similar buildings.

Using NLTHA, in presence of FEMA P695 ground motion records, the maximum story drifts of mass centers, stiff and flexible edges are compared in symmetric and asymmetric buildings. Results show that in buildings with mass eccentricity of 0% and 5%, maximum story drifts in flexible edges in the first, fifth and the sixth stories are equal or greater than those in the stiff edges, while in the other stories are equal or less than those in the stiff edges, which are shown in figures 3 and 4, respectively. In buildings with mass eccentricity of 15% and 25%, maximum story drifts in flexible edges, are greater than those in the stiff edges and mass centers in average (See figures 5 and 6).

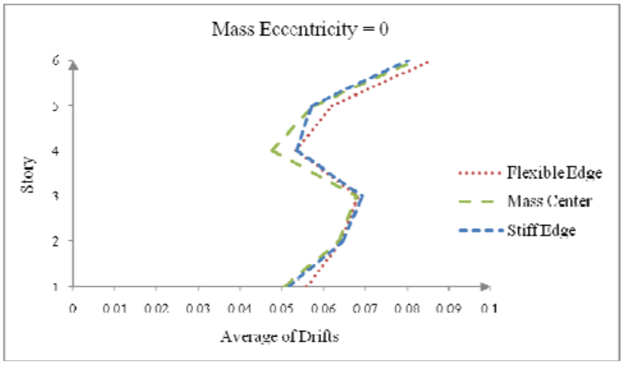

Figure 3. The average value of maximum story drifts in mass centers, stiff and flexible edges in a regular building in presence of 22 earthquake records

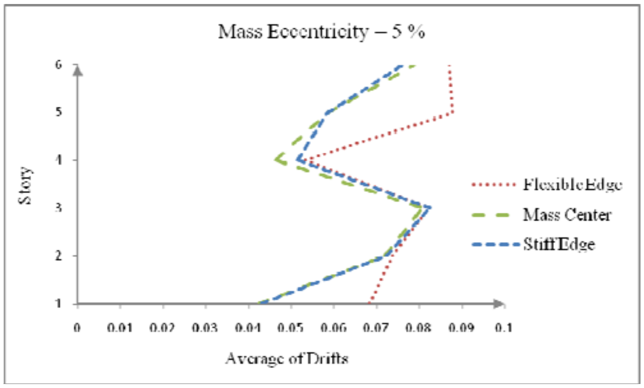

Figure 4. The average value of maximum story drifts in mass centers, stiff and flexible edges in an irregular building with mass eccentricity of 5% in presence of 22 earthquake records

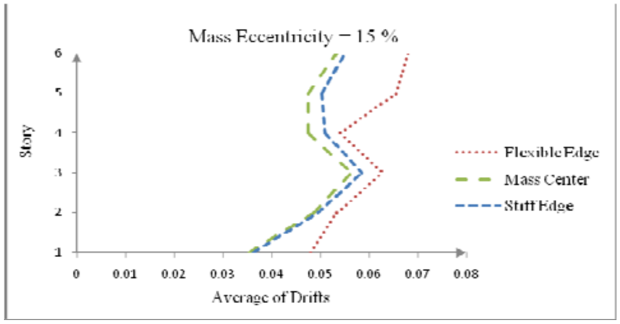

Figure 5**.** The average value of maximum story drifts in mass centers, stiff and flexible edges in an irregular building with mass eccentricity of 15% in presence of 22 earthquake records

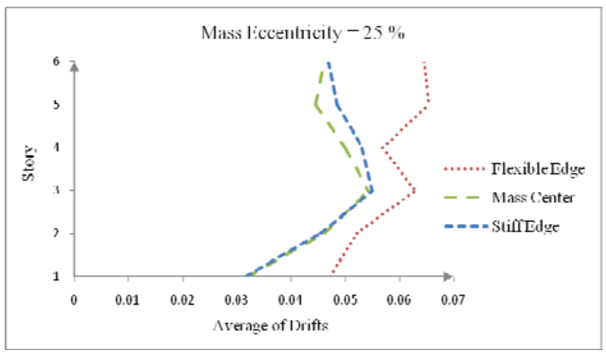

Figure 6**.** The average value of maximum story drifts in mass centers, stiff and flexible edges in an irregular building with mass eccentricity of 25% in presence of 22 earthquake records

As Figures 3, 4, 5 and 6 show, the behavior of the buildings in the mass centers is similar to the stiff edges in 80% of earthquake records.

THE DAMAGE PATTERN

The percentage of increase in the story drifts in mass centers, stiff and flexible edges with increasing the mass eccentricity of the building models are shown in Figure 7 separately, and their average are shown in Figure 8.

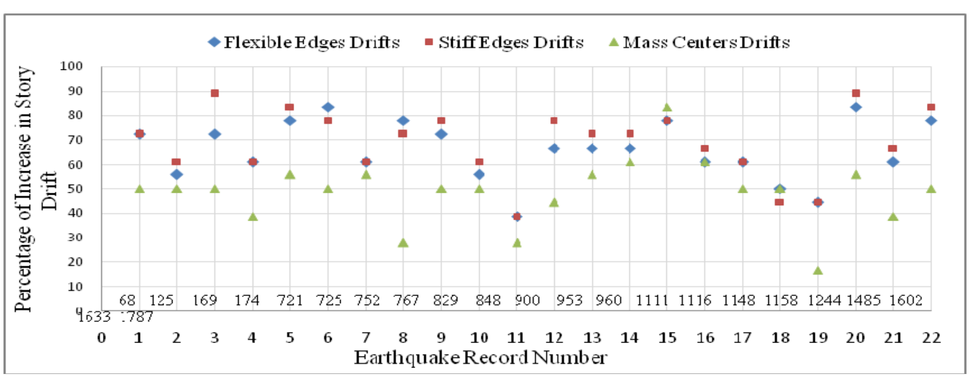

Figure. 7 The percentage of increase in story drift in mass centers, stiff and flexible edges with increase in the mass eccentricity

The percentages of increase in the story drifts in mass centers, stiff and flexible edges are shown in Figure 8. According to this to figure, with increasing the mass eccentricity, the percentages of increase in the story drifts in stiff edges are greater than the story drift in mass centers and flexible edges. This figure also shows that the percentages of increase in story drift of mass centers are less than the story drift in flexible edges.

Averaging over the maximum story drifts in the mass centers, stiff and flexible edges due to 22 earthquake records in different mass eccentricity is shown in figure 8.

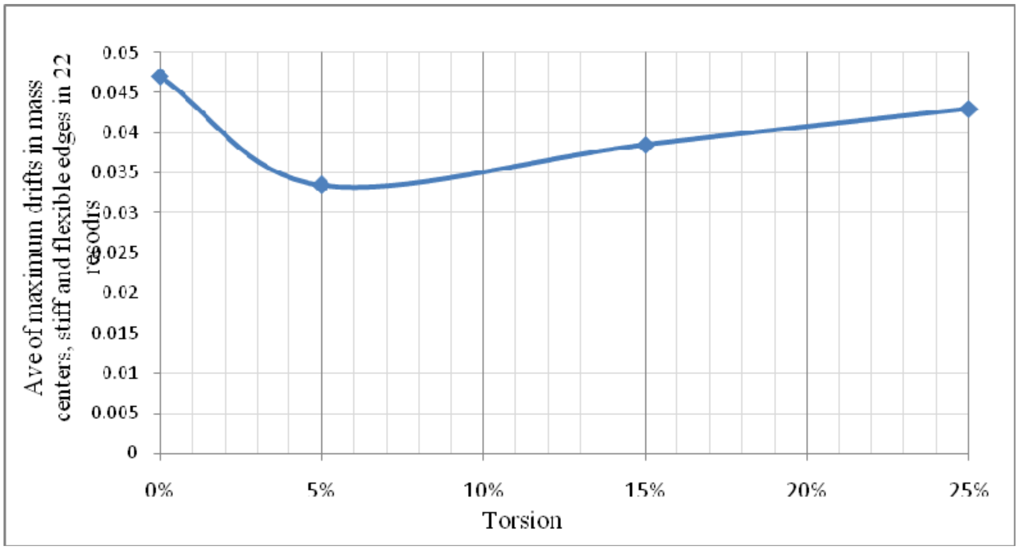

Figure. 8 The average of maximum story drift in mass centers, stiff and flexible edges with increase in the mass eccentricity

Based on the figure 8, when mass eccentricity increases from 5% to 25%, the average of maximum drifts in the mass centers, stiff and flexible edges in presence of 22 earthquake records, increases too.
As Figure 9 shows, with increasing the mass eccentricity, in majority of records, the percentages of decrease in the number of collapsed hinges in the whole of the buildings are greater than the percentages of increase in drifts of the mass centers, and are similar to the percentages of increase in drifts of the stiff and flexible edges. In other words, the trend of decrease in the beam and column collapsed hinges is similar to the trend of increase in the story drifts of the stiff and flexible edges.

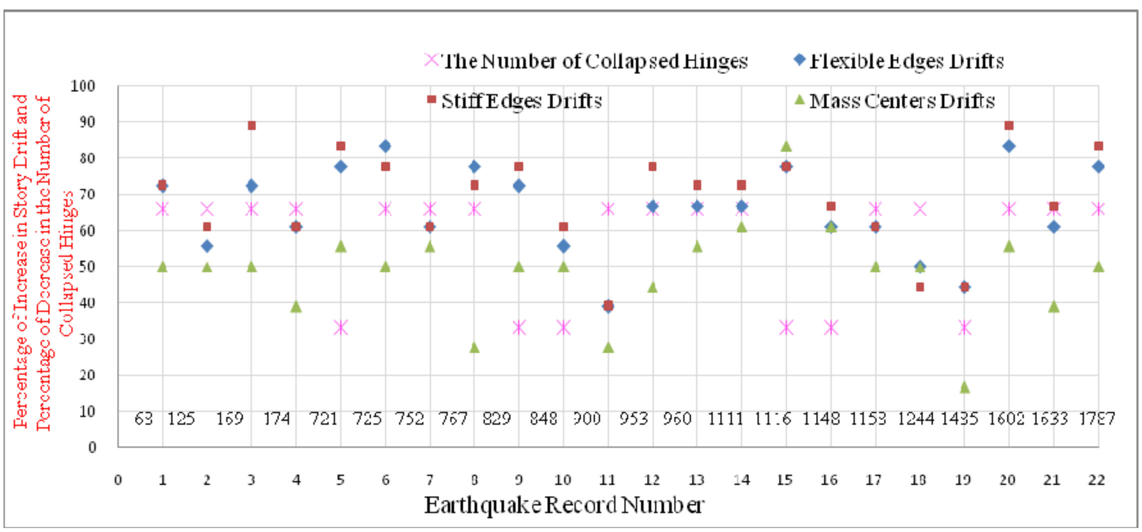

Figure. 9 The percentage of the number of collapsed hinges and story drifts increase in the mass centers, stiff and flexible edges with increase in the mass eccentricity in plan

CONCLUSIONS

--Evaluation of the progressive collapse in 6-story symmetric and asymmetric reinforced concrete ordinary moment resisting frame buildings shows that the building behaviour with respect to the decrease in the number of collapsed beam and column hinges is similar to the trend in the average of maximum story drifts in the mass centres, stiff and flexible edges.
--Collapse propagation process depends on the variation of the mass eccentricity values and is independent of the ground motion records.
--In buildings with 0%, 5% and 15% of the mass asymmetry, collapse horizontally propagates through the stories but in buildings with 25% of the mass eccentricity, it vertically propagates through the height of the buildings.
-- There is more likely that collapse initiate in the flexible edges of irregular buildings.
--In buildings with mass eccentricity of 0% and 5%, maximum story drifts in flexible edges in the first, fifth and the sixth stories are equal or greater than those in the stiff edges, while in the other stories are equal or less than those in the stiff edges, moderately.
--For 80% of the results, the story drifts behaviour in the mass centers is similar to those given by the stiff edges.

ACKNOWLEDGMENT

This study is supported by IIEES Grant No. 479. This support is greatly appreciated.

REFERENCES

Burnett, E.F.P., (1975a), “Abnormal Loading and Building Safety,” American Concrete Institute, International Concrete Research & Information Portal, SP 48, 141-190

Ellingwood, B., (2006). “Mitigating Risk from Abnormal Loads and Progressive Collapse.” J. Perform. Constr. Facil. 20, SPECIAL ISSUE: Mitigating the Potential for Progressive Disproportionate Structural Collapse, 315–323.

FEMA P695. (2009). Quantification of Building Seismic Performance Factors. Prepared by Applied Technology Council, www.ATCouncil.org.

Ibarra, L. F., Medina, R. A., and Krawinkler, H. (2005). “Hysteretic Models that Incorporate Strength and Stiffness Deterioration.” J. Earthquake Eng. and Struct. Dyn.,34, 1489–1511.

Kim,J., and Hong, S. (2011). “Progressive collapse performance of irregular buildings.” Journal of the structural design of tall and special buildings, 20 (6), pages 721–734.

Somes, N. F., (1973), “Abnormal Loading on Buildings and Progressive Collapse,” in Building Practices for Disaster Mitigation (Wright, Kramer and Culver, eds.), Building Science Series No. 46, National Bureau of Standards, Washington, DC.

Tsai Meng-Hao, Lin Bing-Hui , (2008),“Investigation of progressive collapse resistance and inelastic response for an earthquake-resistant RC building subjected to column failure.” J of Engineering Structures, 30(12) , Pages 3619–3628, ELSEVIER