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Seismic Fragility Assessment of Special Truss Moment Frames (STMF) Using the Capacity Spectrum Method

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Abstract: Fragility curves represent the probabilities that structural damages, under various levels of seismic excitation, will exceed the specified damage states by means of earthquake intensity damage relations. Conceptual aspects related to seismic vulnerability, damage and risk evaluation are discussed first, together with a short review of the most widely used possibilities for the seismic evaluation of structures. The capacity spectrum method starting from capacity and fragility curves is then discussed. The determination of capacity curves for buildings using a non-linear structural analysis tools is then explained, together with a simplified expeditious procedure allowing the development of fragility curves. Next, the seismic risk of the special truss moment frame (STMF) systems of Tehran, the capital of Iran, is analysed in this paper using the capacity spectrum method. The seismic hazard of the studied area is described by using the reduced 5%-damped elastic response spectra. Significant damage is obtained for mid-rise and high-rise special truss moment frames with a Vierendeel middle panel, because of the buckling and early fracture of truss web members. Special truss moment frames with an X-diagonal middle segment also show a low seismic capacity leading to significant expected damage.

Keywords: Capacity Spectrum, Damage Evaluation, Fragility Curve, Seismic Risk, Seismic Vulnerability, Special Truss Moment Frame

INTRODUCTION

The special truss moment frame (STMF) is a relatively new type of steel framing system developed for use in areas of high seismicity. This frame dissipates earthquake energy through ductile special segments located near the mid-span of the truss girders (Figure 1). STMFs generally have a good structural redundancy because four plastic hinges can form in the chords of each truss girder. Goel and Itani (1994) studied the potential of using an X-diagonal system for STMFs with X-type diagonals. Their findings showed that the proposed system can be an excellent and efficient seismic resistant framing system for certain classes of building structures. Basha and Goel (1995) investigated the potential use of a Vierendeel segment to dissipate earthquake energy. They concluded that the responses of the sub-assemblages under only lateral loads, as well as under combined gravity and lateral loads are stable with no pinching and degradation.

The aim of risk studies is to estimate the expected damage of structures under a specified earthquake hazard level at a territorial scale, for instance, an urban area. There are a number of methodologies for estimating the vulnerability, damage and risk in seismic areas. Almost all of these methodologies have difficulties arising from the lack or low quality of available data when they are applied in low-to-

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moderate seismic areas. Building modelling and non-linear structural analysis are two methods of compensating for the shortage of data (Milutinovic and Trendafiloski, 2003; Barbat et al., 2006a; Barbat et al., 2006b). In areas without any available damage databases, the information obtained in other similar areas is applied as well as an expert judgment. Accordingly, the probabilistic analysis of computer-generated structural responses, obtained by nonlinear analysis of representative buildings, has provided fragility curves, damage probability matrices and vulnerability functions.

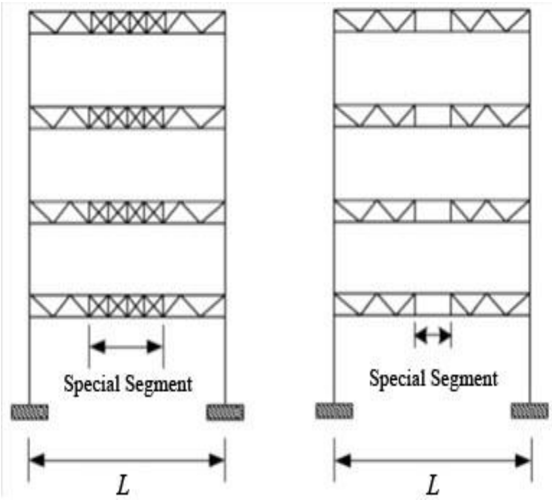


Fig. 1. Typical special truss moment frames (Basha and Goel, 1995).

In a recent study on the truss moment frames, Longo et al. (2012) investigated a new approach for designing Dissipative Truss Moment Frames (DTMFs) under seismic forces. Wongpakdee et al. (2012) designed buckling restrained knee braced truss moment frames using the performance-based seismic design method and evaluated its performance. Yang et al. (2014) tried to optimize the buckling restrained knee braced truss moment frames.

There are certain aspects involved in the seismic damage evaluation of an urban area which should be pointed out:

1. High uncertainties are associated with each step of seismic risk evaluation, particularly in the evaluation of seismic hazards in low-to-moderate seismic areas and in the vulnerability assessment of existing buildings. It is not the purpose of this paper to perform a probabilistic study in the strict sense, but to perform analyses based on average or most likely values.

2. For management purposes, risk analysis requires a multidisciplinary procedure that takes into account not only the expected physical damage, the number and the type of casualties, and the economic losses, but also the conditions related to social fragility and lack of resilience, which favour the indirect effects when a hazard event strikes an urban centre (Carren et al., 2007a; Carren et al., 2007b). In this paper, only the physical risk of urban areas is studied.

3. The most recent trends in vulnerability evaluation for risk analysis operate with simplified mechanical models essentially based on the capacity spectrum method (HAZUS 99-SR2, 2002; Freeman, 1978; Freeman, 1998), and this is the method used in this study. The method permits the expected seismic performance of structures to be evaluated by comparing, in spectral coordinates, their seismic capacity with the seismic demand, described by acceleration-displacement response spectra (ADRS) adequately reduced in order to take into account inelastic behaviour (Faccioli, 2000; Fajfar, 2002). To develop damage and risk scenarios, capacity spectra and fragility curves have been developed and applied to simulate earthquake risk scenarios.

CAPACITY SPECTRUM METHOD

The capacity spectrum method has been used in this paper to estimate the expected performance of the special truss moment frames of Tehran under specified earthquake scenarios. The earthquake ground motion is represented by means of 5% damped elastic response spectra. A non-linear macro-element model has been used to model the special truss moment frames. The AISC Seismic Provisions (AISC, 2007) and IBC provisions (International Building Code, 2006) include design specifications, obtained by analytical and experimental studies (Hanson et al., 1971; Itani and Goel, 1991; Basha and Goel, 1994), for STMFs. Located in the central half of each truss, the special segments are designed to withstand large inelastic deformations during seismic events. This controlled inelastic action limits forces on all elements outside the special segment to the ultimate capacity of the middle (special) segment.

Capacity curves are obtained, in this case, by using the computer code SAP2000 (Structural Analysis Program, 2000). Studied structures are modelled by means of several plane frames connected to one another. The obtained capacity curves are represented in the same spectral acceleration (Sa)–spectral displacement (Sd) domain as the demand spectrum. Finally, these curves have been described in a bilinear form defined by yielding (D_y, A_y) and ultimate (D_u, A_u) points. The performance point is determined by using the iterative method (procedure A) of the ATC-40 (1996) code.

To analyse the seismic damage, five damage states are considered: none, slight, moderate, severe and complete. A weighted average damage index, DS_m can be calculated as:

$$DS_m = \sum_{i=0}^{4} ds_i P[ds_i] \qquad (1)$$

where ds_i: takes the values 0, 1, 2, 3 and 4 for the damage states i considered in the analysis, and $P[ds_i]$: is the corresponding occurrence probabilities.

Table 1 shows the most probable damage state as a function of the average damage index, DS_m. This damage index is useful for mapping and analysing damage distributions by using a single parameter.

Table 1. Mean damage index values and corresponding damage states.

Mean Damage Index Intervals	More Probable Damage State
0–0.5	No damage
0.5–1.5	Slight damage
1.5–2.5	Moderate damage
2.5–3.5	Severe damage
3.5–4.0	Complete damage

Fragility curves define the probability that the expected global damage d of a structure will exceed a given damage state ds_i ($P[d \geq ds_i]$) as a function of the severity of seismic action (e.g., spectral displacement, Sd). Assuming that fragility curves follow a lognormal probability distribution, they can be completely defined by two parameters, namely the mean spectral displacement $\overline{Sd}_{ds_i}$ and the standard deviation β_{ds_i}, as:

$$P[\frac{d_{si}}{Sd}] = \Phi[\frac{1}{\beta_{dsi}} \ln(\frac{Sd}{\overline{\overline{Sd}}_{dsi}})] \qquad (2)$$

where $\overline{Sd}_{ds_i}$: is the threshold spectral displacement at which the probability of the damage state, ds_i, is 50%, β_{ds_i}: is the standard deviation of the natural logarithm of the spectral displacement, and Φ: is the standard normal cumulative distribution.

Fragility curves can be obtained in a simplified manner starting from the bilinear representation of the capacity curves. Table 2 and Figure 2 show how the thresholds $\overline{Sd}_{ds_i}$ are obtained in this case as a function of the yielding displacement D_y and the ultimate displacement D_u of the structure.

Table 2. Damage state thresholds (see Figure 2).

$\overline{Sd}_{ds_i}$	**Damage State**
$\overline{Sd_1} = 0.7D_y$	Slight
$\overline{Sd_2} = D_y$	Moderate
$\overline{Sd_3} = D_y + 0.25(D_u - D_y)$	Severe
$\overline{Sd_4} = D_u$	Complete

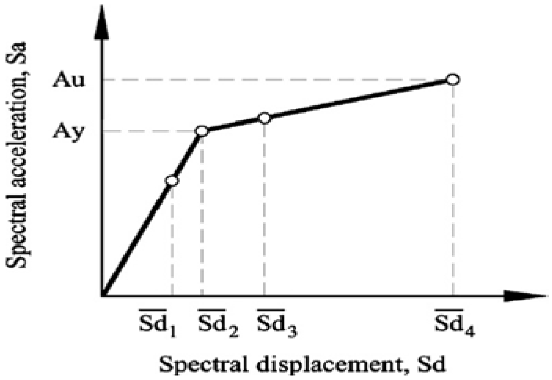


Fig. 2. Damage state thresholds and the capacity spectrum (Shinozuka et al., 2001).

The dual parameter β controlling the distribution function is obtained using the well-known Maximum Likelihood Method (Shinozuka et al., 2001). Statistical procedures as described by Shinozuka et al. (2001) are applied to test the goodness of the fit of the estimated fragility curves to the results of individual simulations. The analyses have shown that the values of parameter β estimated for the construction of fragility curves are the true values with a significance level of 10%.

THE STRUCTURAL CAPACITY OF SPECIAL TRUSS MOMENT FRAMES

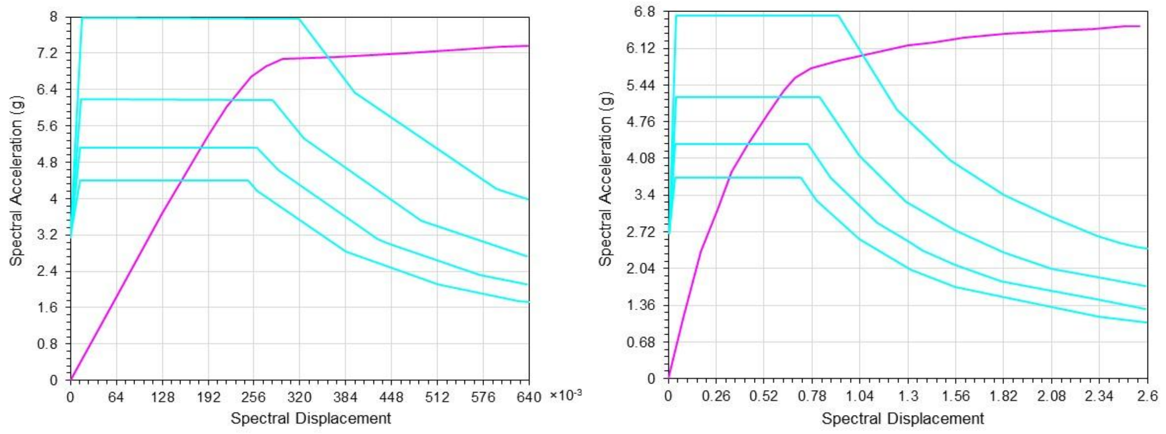
The seismic performance of a building can be characterized by its bilinear capacity spectrum, obtained by means of a pushover analysis (ATC-40, 1996). Detailed structural plans are used to model representative buildings for mid-rise (three storey, 18.0m tall) and high-rise (five storey, 30.0 m tall) special truss moment frames. Capacity curves are obtained by performing non-linear static analyses using the SAP2000 software. Structures are modelled by means of several plane frames connected to one another. High-rise and mid-rise frames have a rectangular floor size of 36.0 m × 18.0 m. The following mean mechanical properties are assumed: steel yield stress $f_y = 240MPa$, elastic modulus $E_s = 210GPa$, and shear modulus $G = 80GPa$.

As capacity curves are based on the assumption that the response of the structure is dominated by the fundamental mode of the vibration, they describe adequately the seismic behaviour of buildings with a fundamental period lower than 1.5 s (ATC-40, 1996). Pushover analyses allow the capacity curves for each STMF class to be determined, and, starting from these curves, capacity spectra can be obtained (ATC-40, 1996). Table 3 shows the fundamental period and the yield and ultimate capacity points of the bilinear capacity spectra for the modelled special truss moment frames. The ranges of the number of floors for the corresponding STMF classes have also been included in Table 3.

Figures 3 and 4 show the capacity spectra for special truss moment frames with the 5% damped elastic response spectra in the ADRS format. It is observed that the crossing points are performance points only when they belong to the linear branch of the capacity curves. However, even when they are on the nonlinear branch, a graphical estimate of the performance point can be visualized by taking into account the equivalent linear displacement method. This fact becomes important when evaluating damage by using fragility curves because it greatly influences the damage probability matrices. A significant ductility can be observed for mid-rise and high-rise special truss moment frames. In Figures 3 and 4, it can also be seen how capacity decreases with the increase in the height of the special truss moment frames. The 5% damped elastic response spectra in ADRS format are also shown for probabilistic cases.

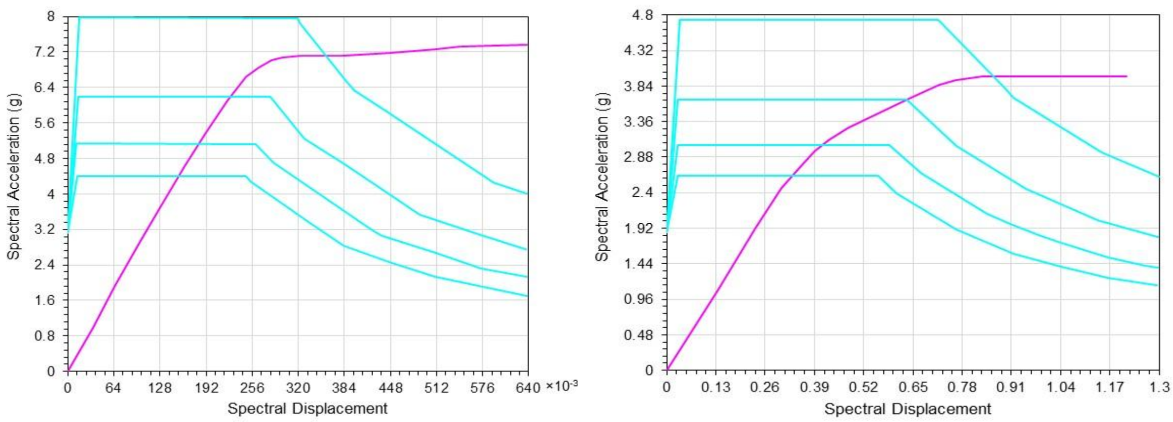
Table 3. Yield and ultimate capacities for special truss moment frames.

Building class	Range of Number of Floors	Period (s)	$D_y(cm)$	$A_y(g)$	$D_u(cm)$	$A_u(g)$
Mid-rise, STMF with Vierendeel middle panel	2–4	0.76	24.0	4.42	72.5	7.51
High-rise, STMF with Vierendeel middle panel	5+	1.23	32.5	2.83	91.0	4.69
Mid-rise, STMF with X-diagonal middle segment	2–4	0.76	22.4	7.47	64.7	10.02
High-rise, STMF with X-diagonal middle segment	5+	1.23	24.2	3.73	86.2	6.15



(a) **(b)**

Fig. 3. Capacity spectra for special truss moment frames with X-diagonal middle segment, a) Mid-rise frame, b) High-rise frame.



(a) **(b)**

Fig. 4. Capacity spectra for special truss moment frames with Vierendeel middle panel, a) Mid-rise frame, b) High-rise frame.

FRAGILITY CURVES OF SPECIAL TRUSS MOMENT FRAMES

Specific fragility curves, shown in Figures 5 and 6, have been developed for special truss moment frames. Table 4 lists the values of the parameters $\overline{Sd}_i$ and β_i, which define the corresponding cumulative lognormal distribution (Eq. (2)), for $i = 1,...,4$. It can be observed that the STMF with X-diagonal middle segment is more ductile than the STMF with a Vierendeel middle panel, and, hence, the former shows a better seismic performance. For example, for the mid-rise special truss moment frame with an X-diagonal middle segment in Figure 5a, in case of a 40 cm spectral displacement, the expected probability for the complete damage state is about 5%, but it is more than 10% for STMF with Vierendeel middle panels (Figure 6a). Unfortunately, Tehran is located in an area with a high level of seismic hazard. So the analysis clearly reveals the very high vulnerability of the buildings and, consequently, a significant probability of damage even in the case of a not too severe earthquake. It is somewhat surprising that the obtained results show a high expected seismic damage for relatively low spectral displacements.

Table 4. Parameters characterizing the fragility curves, for STMF with X-diagonal middle segment (STMF-X) and STMF with a Vierendeel middle panel (STMF-V).

STMF Class	Damage States Thresholds							
	$\overline{Sd}_1(cm)$	β_1	$\overline{Sd}_2(cm)$	β_2	$\overline{Sd}_3(cm)$	β_3	$\overline{Sd}_4(cm)$	β_4
Mid-rise, STMF-X	18	0.38	24	0.47	35	0.62	72	0.73
High-rise, STMF-X	24	0.38	29	0.39	42	0.46	81	0.56
Mid-rise, STMF-V	15	0.5	21	0.61	35	0.86	72	0.80
High-rise, STMF-V	19	0.40	23	0.75	38	0.75	76	0.75

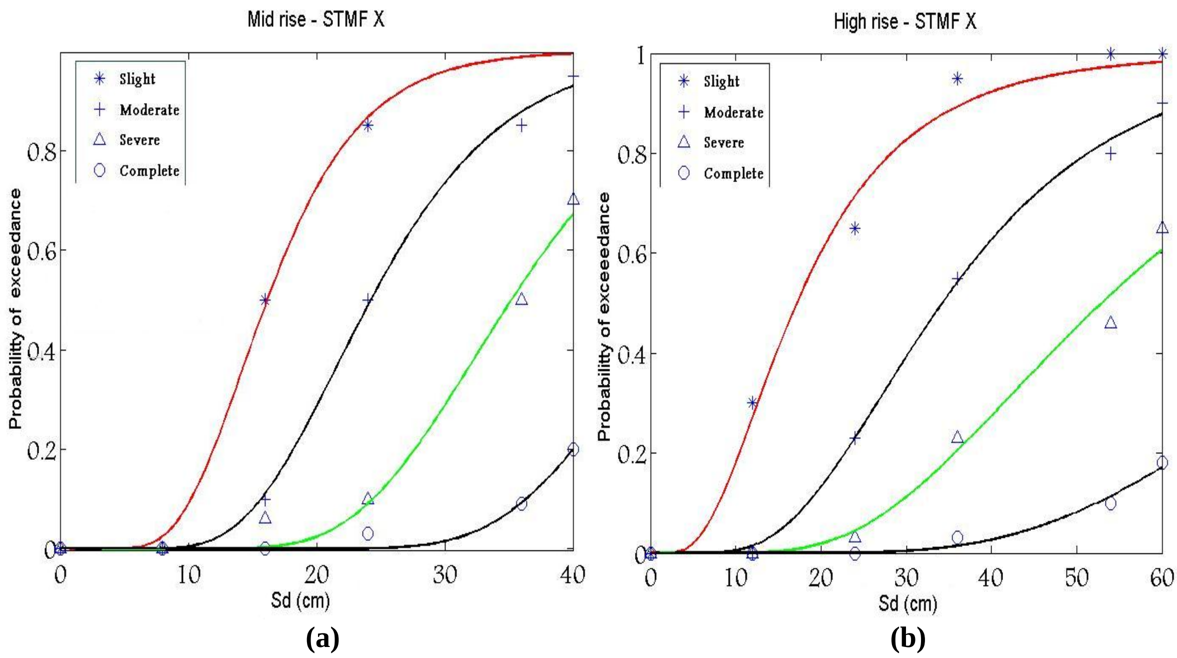
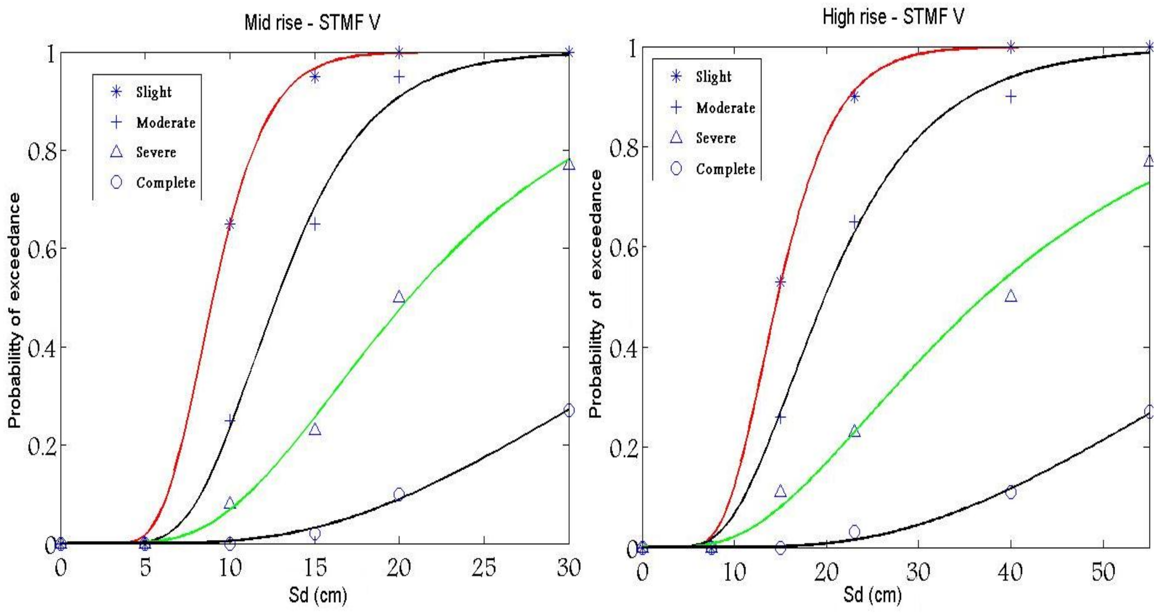


Fig. 5. Fragility curves for special truss moment frames with an X-diagonal middle segment, a) Mid-rise frame, b) High-rise frame.



(a) **(b)**

Fig. 6. Fragility curves for special truss moment frames with a Vierendeel middle panel, a) Mid-rise frame, b) High-rise frame.

CONCLUSIONS

The seismic risk evaluation method used in this paper incorporates last generation methodologies for hazard, damage and risk estimation. The vulnerability of the different special truss moment frame classes is characterized by bilinear capacity spectra obtained by using CMS methods. Using the capacity spectra, fragility curves are also estimated in a simplified way for each considered special truss moment frame type. The adopted method has been applied to Tehran, a typical Mediterranean city located in an area of high seismic hazard.

As one of the most important findings of the present study, significant damage is observed for mid-rise and high-rise special truss moment frames with a Vierendeel middle panel, because of the buckling and early fracture of truss web members. Special truss moment frames with X-diagonal middle segment also show low seismic capacity leading to significant expected damage. In comparison between the STMF with X-diagonal and the Vierendeel middle panel, it can be observed that the STMF with an X-diagonal middle segment is more ductile than the special truss moment frame with a Vierendeel middle panel, and, hence, the former shows a better seismic performance. For example, for mid-rise special truss moment frames with an X-diagonal middle segment, in case of a 40 cm spectral displacement, the expected probability for the complete damage state is about 5%, but it is more than 10% for STMF with Vierendeel middle panels.

REFERENCES

American Institute of Steel Construction (AISC). (2007). *Specification for Structural Steel Buildings*, Chicago (IL), AISC.

ATC-40. (1996). *Seismic evaluation and retrofit of concrete buildings*, Report No: SSC 96-01. Applied Technology Council, Vol. 1, Redwood City, CA: Seismic Safety Commission.

Barbat, A.H., Pujades, L.G. and Lantada, N. (2006a). “Performance of buildings under earthquake in Barcelona, Spain”, *Computer Aided Civil Infrastructures Engineering*, 21(8), 573–593.

Barbat, A.H., Lagomarsino, S. and Pujades, L.G. (2006b). “Vulnerability assessment of dwelling buildings", Oliveira, C.S., Roca, A. and Goula, X. (eds.), *Assessing a Managing Earthquake Risk*, Dordrecht, the Netherlands, Springer, 115–134.

Basha, H. and Goel, S.C. (1994). *Seismic resistant truss moment frames with ductile vierendeel segment*. Report No. UMCEE 94-29, Ann Arbor, Department of Civil and Environmental Engineering, University of Michigan.

Basha, H.S. and Goel, S.C. (1995). "Special truss moment frames with vierendeel middle panel", *Engineering Structures*, 17(5), 352-358.

Carreno, M.L., Cardona, O.D. and Barbat, A.H. (2007a). "Urban seismic risk evaluation: a holistic approach", *Natural Hazards*, 40(1), 137–172.

Carreno, M.L., Cardona, O.D. and Barbat, A.H. (2007b). "Disaster risk management performance index", *Natural Hazards*, 41(1), 1–20.

Faccioli, P. (2000). "A nonlinear analysis method for performance-based seismic design", *Earthquake Spectra*, 16(3), 573–5924.

Fajfar, P. (2002). "Structural analysis in earthquake engineering- a breakthrough of simplified nonlinear methods", *Proceedings of the 12th European Conference on Earthquake Engineering*, London, Paper No. 843.

Freeman, S.A. (1978). "Prediction of response of concrete buildings to severe earthquake motion", *Proceedings of Douglas McHenry International Symposium on Concrete and Concrete Structures*, Publication SP-55, Detroit, MI, USA, American Concrete Institute.

Freeman, S.A. (1998). "The capacity spectrum method", *Proceedings of the 11th European Conference on Earthquake Engineering*, Paris.

Goel, S.C. and Itani, A.M. (1994). "Seismic-resistant special truss-moment frames", *Journal of Structural Engineering*, ASCE, 120(6), 1781-1797.

Hanson, R.D., Goel, S.C. and Berg, G. (1971). *Seismic behaviour and design procedure of staggered truss frame system for earthquake loading*, Report No. 175, Ann Arbor, Department of Civil and Environmental Engineering, University of Michigan.

HAZUS 99-SR2 (2002). *HAZUS technical manual*, Vol. 1–3, Washington, DC, Federal Emergency Management Agency, FEMA and National Institute of Building Sciences, NIBS.

Itani, A.M. and Goel, S.C. (1991). *Earthquake resistance of open web framing systems*, Report No. UMCEE 91-21, Ann Arbor, Department of Civil and Environmental Engineering, University of Michigan.

International Building Code (IBC) (2006). *International Codes Council*, Falls Church, Whittier, CA, USA.

Longo, A., Montuori, R. and Piluso, V. (2012). "Failure mode control and displacement based design of dissipated truss moment frames: Seismic performance evaluation", *Proceedings of the 15th World Conference of Earthquake Engineering*, Lisbon, Portugal.

Milutinovic, Z.V. and Trendafiloski, G.S. (2003). *Vulnerability of current buildings*, Work Package 4 of RISK-UE Project. European Commission, EVK4-CT-2000-00014.

Shinozuka, M., Feng, M.Q., Kim, H., Uzawa, T. and Ueda, T. (2001). *Statistical analysis of fragility curves*, Report No. 106-E-7.3.5 and 106- E-7.6. Technical Report MCEER. Department of Civil and Environmental Engineering, University of Southern California.

Structural Analysis Program, SAP (2000). Computers and Structures Inc., Berkeley, California.

Wongpakdee, N., Leelataviwat, S., Goel, S.C. and Liao, W.C. (2012). "Performance-based seismic design and evaluation of Bucklinbg restrained knee braced truss moment frames", *Proceedings of the 15th World Conference of Earthquake Engineering*, Lisbon, Portugal.

Yang, T.Y., Yuanjie, Li. and Leelataviwat, L. (2014). "Performance-based design and optimization of buckling restrained knee braced truss moment frame", *Journal of Performance of Constructed Facilities*, ASCE, 28(6), A4014007.