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Comparison of Seismic and Gravity Progressive Collapse in dual systems with special steel moment-resisting frames and braces

Maryam Musavi-Z [a], Mohammad Reza Sheidaii [b,*]

[a] *Ph.D. Candidate, Department of Civil Engineering, Urmia University, Urmia, Iran*
[b] *Professor, Department of Civil Engineering, Urmia University, Urmia, Iran*

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ABSTRACT:

Progressive collapse studies generally assess the performance of the structure under gravity and blast loads, while earthquakes may also lead to the progressive collapse of a damaged structure. In this study, the progressive collapse response of concentrically braced dual systems with steel moment-resisting frames was assessed under seismic loads through pushover analysis using triangular and uniform lateral load patterns. Two different bracing types (X and inverted V braces) were considered, and their performances were compared under different lateral load patterns using the nonlinear static alternate path method recommended in the Unified Facilities Criteria (UFC) guideline. Eventually, the seismic progressive collapse resistance of models was compared to their progressive collapse response under gravity loads. These studies showed that models under the seismic progressive collapse loads satisfied UFC acceptance criteria and limited rehabilitation objective. The structures had better performance under seismic progressive collapse than models under gravity loads because of more resistance, ductility, suitable load redistribution, and more structural elements that participated in load redistribution. Furthermore, despite studies on progressive collapse under gravity loads, the dual system with X braces showed better progressive collapse performance (more resistance, residual reserve strength ratio and ductility) under seismic loads than the model with inverted V braces.

KEYWORDS:

Seismic progressive collapse, Dual system, Concentric brace, Alternate path method, Nonlinear static analysis

1. Introduction

Progressive collapse spreads from an initial local failure in an element to other elements leading to disproportionate collapse of structure (ASCE 7, 2005). In progressive collapse-resistant design, a structure shall be capable of withstanding abnormal loads, such as fires, explosions, and vehicular impact, without disproportionate failure (ASCE 7, 2010). Collapses of Ronan Point building in 1968, Murrah Federal Building in 1995, and World Trade Center in 2001 are popular examples of progressive collapse events around the world (Li et al., 2016).

Progressive collapse is a rare phenomenon with significant casualties (UFC, 2016). After the collapse of the Ronan Point tower in 1968, many codes such as NIST (2008), ASCE 7 (2005), and ACI 318 (2005) noted the importance of designing structures against progressive collapse, and GSA (2003) and UFC (2005) guidelines were written to design structures under progressive collapse loads.

The alternate path method is the most common design method of progressive collapse (Kiakojouri et al., 2020a). In this procedure, a critical structural element is removed, and resistance of structure under progressive collapse load combination is assessed (UFC, 2016).

Various studies investigated the advantages and disadvantages of progressive collapse analysis methods (Marjanishvili and Agnew, 2006; Kim and Kim, 2009). Some of the progressive collapse researches considered different seismic force-resisting systems to assess their progressive collapse response under abnormal gravity loads, such as steel moment-resisting frame (Kim and Kim, 2009; Hosseini et al., 2014; Yousefi et al., 2014; Mahmoudi et al., 2016; Ghobadi et al., 2018; Kiakojouri et al., 2020b), different concentrically

* Corresponding Author
E-mail addresses: m.sheidaii@urmia.ac.ir (Mohammad Reza Sheidaii), m.musaviz@urmia.ac.ir (Maryam Musavi-Z).

and eccentrically braced frames (Khandelwal et al., 2009; Kim et al., 2011), cross-bracing systems (Fu, 2010), Special truss moment frames (Kim and Park, 2014) and composite frame buildings (Fu, 2010, 2012; Guo et al., 2015; Wang et al., 2019; Galal et al., 2019; Suwondo et al., 2019).

The progressive collapse phenomenon is not limited only to gravity and blast loads. It may also occur during earthquakes. The occurrence of an earthquake can cause local damage to the structure. Then the structure with the local failure reaches equilibrium condition, and the incidence of an after-shock may cause the progressive collapse in the damaged structure (Tavakoli and Rashidi Alashti, 2013). There are fewer studies of progressive collapse under earthquake loads. Park and Kim (2010) demonstrated that designing buildings under seismic loads leads to low vulnerability of structure for progressive collapse. Wibowo and Lau (2009) stated that current progressive collapse studies generally focus on progressive collapse under blast and abnormal gravity loads, and progressive collapse of structures under seismic loads has not received as much attention. Tavakoli and Rashidi Alashti (2013) studied the seismic progressive collapse resistance of moment-resisting steel frames using pushover analysis. It was found that models resisted progressive collapse under lateral loading in one column loss scenario.

According to the ASCE7 (2016), dual system is a structural system with an essentially complete space frame providing support for vertical loads. Dual system withstands the total seismic force by the combination of the braced frames and moment frames (at least 25%) in proportion to their rigidities. Despite the previous studies regarding the progressive collapse performance of dual systems (Faroughi et al. 2017; Shayanfar and Javidan 2017) or other researches about the impacts of seismic designs on the progressive collapse response of structures (Rezvani and Asgarian 2014; Kordbagh and Mohammadi 2017), the comparison of seismic and gravity progressive collapse of the dual systems is not well understood. In this study, the progressive collapse resistance of the conventional dual systems combined by special steel moment resisting frames and special concentric braces was investigated under seismic loads; by modifying the nonlinear static alternate path method recommended in the UFC (2016) guideline. For this purpose, the performance of different bracing types (X and inverted V braces) was compared under different lateral load patterns. Eventually, seismic progressive collapse resistance of models was compared to gravity progressive collapse resistance.

2. Analyzed structural models

The probability of progressive collapse occurrence which is analyzed using the APM (Alternate Path Method) decreases in the taller buildings. In fact, the high redundancy of taller structures reduces the risk of progressive collapse due to sudden removal of the member in this type of structures. Therefore, the model structure was designed considering fewer stories. The structural models analyzed in this study were 6-story residential buildings. The seismic force-resisting system of structures was dual systems with special steel moment-resisting frames and special concentric braces. Two different types of bracing, including X and inverted V braces, were considered. The buildings had four bays with a length of 6 m. Plan dimensions were 24m×24m, and the height of all stories was 3.2m. The plan layout and the elevation of the structures are shown in Fig. 1 and 2, respectively.

ASCE7 (2016) was employed to obtain seismic design loads. The design spectral acceleration parameter (S_{DS}) was equal to 1g, and the models classified in the seismic design category D. AISC 360 (2016), and AISC 341 (2016) were used to the design of structures. Plastic hinges were assigned to models using FEMA356 (2000), and UFC (2016) recommendations were followed for progressive collapse analysis.

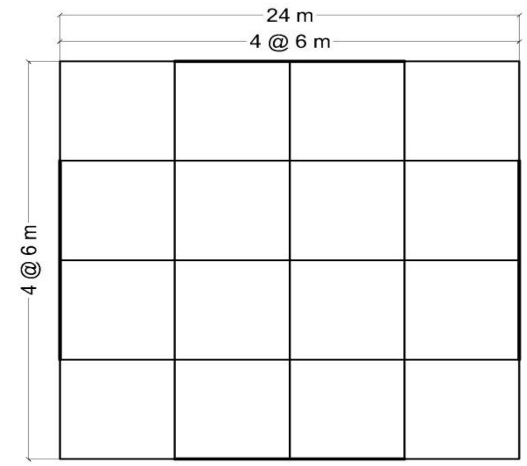
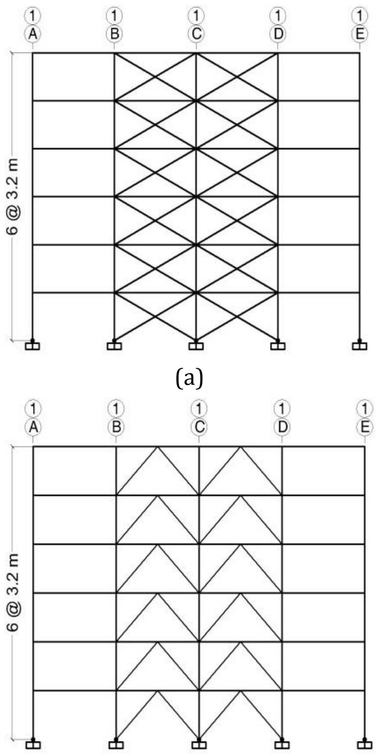


Fig. 1. Plan layout of the model structures.



(a)

(b)

Fig. 2. Elevation of the 6-story model structures: (a) Dual systems with X braces, (b) Dual systems with inverted V braces

The characteristics of the models and their abbreviations are depicted in Table 1. The abbreviation was specified according to the seismic force-resisting system (Dual System), bracing type (X-type, Inverted V-type), and critical element loss (0, 100). Therefore, DSiv0 and DSiv100 are the dual systems with inverted V braces without and with element loss (intact and damaged structures), respectively.

Wide flange sections with young modulus of 29000 ksi made of ASTM A992 steel (F_y = 50 ksi and F_u = 65 ksi) were selected for beams and columns, and seismically compact, square Hollow Steel Sections (HSS) made of A500 steel (E= 29000 ksi, F_y = 50 ksi and F_u = 62 ksi) were used for the braces. Table 2 shows the sections of structural members.

Table 1. Analyzed models characteristics

Model	Seismic force-resisting systems	Critical element loss (%)	Description
DSx0	Dual system with X braces	0	Intact structure (Without element removal)
DSx100		100	Damaged structure (With complete element removal)
DSiv0	Dual system with inverted V braces	0	Intact structure (Without element removal)
DSiv100		100	Damaged structure (With complete element removal)

3. Progressive collapse analysis procedures

For progressive collapse analysis, the nonlinear static alternate path method recommended in the UFC (2016) was used. Pushover and pushdown analyses were carried out using the SAP2000 commercial program (2004) to investigate the seismic and gravity progressive collapse behavior. The structure should satisfy UFC acceptance criteria after removing the critical element. A column near a brace was chosen to assess the impact of simultaneous elimination of a column and its adjacent brace in dual systems similar to research work of Khandelwal et al. (2009).

Fig. 3 shows the location of the removed critical elements (column B1 and its adjacent brace in the first story).

Table 2. Sections of structural members

Story	Column		Beam		Brace
	Internal	External	Internal	External	
1st	W 12×136	W 12×136	W 12×35	W 12×22	HSS 6×6×3/8
2nd					
3rd	W 12×120	W 12×96			
4th					
5th	W 12×96				HSS 5×5×5/16
6th			W 12×19	W 12×19	

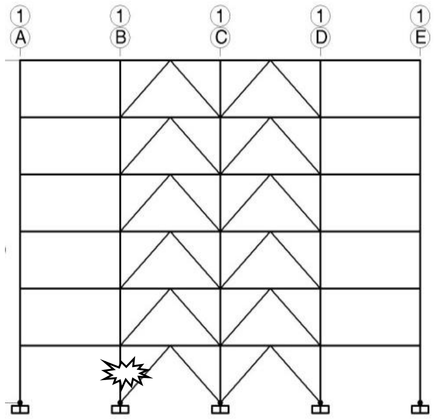


Fig. 3. Location of the removed column and its adjacent brace in the first story

3.1. Pushdown analysis

Pushdown analyses were used to assess the progressive collapse resistance of the models under gravity loads. In this procedure, the vertical displacement above the column loss location was increased gradually to draw pushdown curves.

UFC guideline defines "(1.2D+0.5L)" as the gravity load combination of progressive collapse analyses where *D* and *L* are dead load and live load, respectively. This combination should increase multiplying a dynamic increase factor (Ω_N) on bays adjacent to the missing element and at all floors above it in static alternate path analyses to take into account the dynamic effects of the progressive collapse phenomenon. Dynamic increase factor in the pushdown analysis of steel buildings was calculated using the following equation (UFC, 2016).

$$\Omega_N = 1.08 + 0.76/(\frac{\theta_{pra}}{\theta_y} + 0.830) \quad (1)$$

Where θ_{pra} is the plastic rotation angle and θ_y is the yield rotation. The dynamic increase factor was calculated about 1.17 using θ_{pra} and θ_y amounts recommended by FEMA356 (2000) for nonlinear procedures of steel components. Fig. 4 shows the applied gravity loads for progressive collapse pushdown analysis.

The generalized force-deformation relation of steel elements is shown in Fig. 5 with parameters *a, b,* and c as defined in the FEMA356 (2000). The ratio of the post-yield stiffness to the initial stiffness was assumed to be 3%. Plastic hinges were defined as axial-flexural, flexural and axial for columns, beams, and braces, respectively. Table 3 shows the type and the location of the assigned plastic hinges in SAP2000.

Nonlinear acceptance criteria for structural steel columns and braces must meet the Life Safety performance level, and collapse prevention limit state is recommended for beams (UFC, 2016).

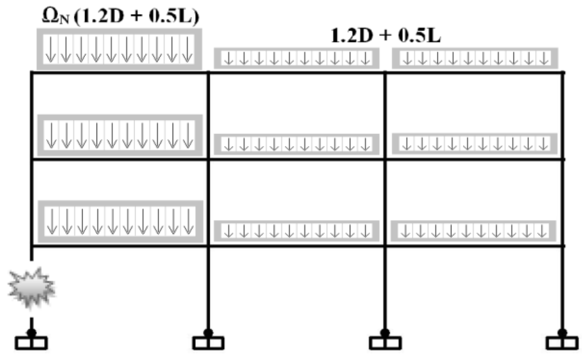


Fig. 4. Imposed gravity loads for progressive collapse analysis (Musavi-Z and Sheidaii, 2021)

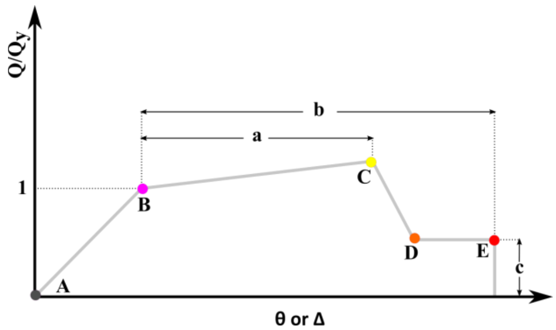


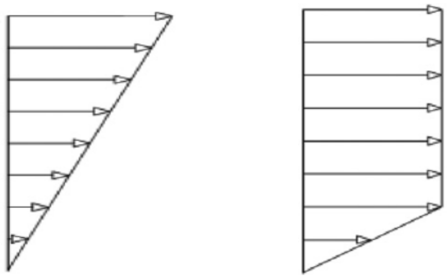
Fig. 5. Generalized force-deformation relation for steel elements or components (Musavi-Z and Sheidaii, 2021)

Table 3. Type and location of the assigned hinges

Element	Type of hinge	Location of hinge
Column	Axial-Flexural (P-M2-M3)	Both ends and middle of columns
Beam	Flexural (M3)	Both ends of beams
Brace	Axial (P)	Middle of braces

3.2. Pushover analysis

In this method, horizontal displacement of the mass center at the roof of model was gradually increased, and the pushover curves were accordingly drawn. The models were checked for UFC acceptance criteria as discussed in the last section and rehabilitation objectives in FEMA356 (2000). The procedure of pushover analysis is similar to pushdown analysis. The dynamic increase factor is neglected (Ω_N is equal to 1) because the damaged structure reached equilibrium condition before the lateral load condition occurs. According to FEMA356 (2000), two types of lateral load distribution patterns (one each time) were used that applied in both the positive and negative directions to the model structure, and the maximum seismic impacts were considered. In this study, triangular and uniform distributions were selected, as shown in Fig. 6. These lateral load patterns were applied in the plane of elements removal because of sever seismic effects due to more attenuation of the dual system by elimination of the column and its adjacent brace and greater torsional moment of earthquake.



(a) (b)

Fig.6. Imposed lateral load patterns for pushover analysis: (a) Triangular pattern, (b) Uniform pattern

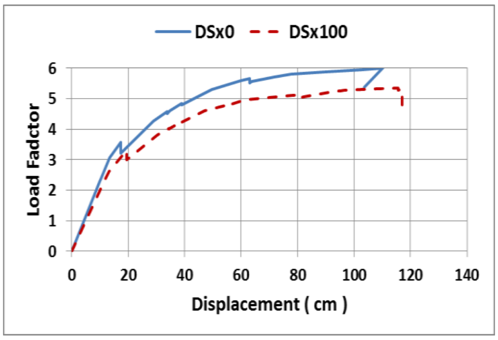
4. Assessment of seismic progressive collapse

The pushover analysis results are provided as load factor-displacement graphs to assess the effects of lateral load patterns and brace configuration types on seismic progressive collapse response of model structures. The ratio of the applied load to the design base shear is defined as the load factor in the vertical axis of graphs. The horizontal axis of the diagrams refers to the horizontal displacement of the mass center in the highest roof. Load factor-displacement relations for triangular and uniform lateral load in positive and negative directions are shown in Fig. 7 and 8 for DSx and DSiv models, respectively. The progressive collapse resistance and corresponding displacement of models are shown in Table 4.

The progressive collapse resistance of the structure defines as the maximum load factor satisfying UFC acceptance criteria, and the structures with the progressive collapse resistance of at least one can resist progressive collapse loads. In fact, this factor indicates that the structure is able to withstand multiple progressive collapse loads, but it cannot describe the amount of capacity reduction in damaged structures. For this purpose, a robustness indicator is used. Insensitivity to local failure defines robustness (Tavakoli and Rashidi Alashti, 2013). If the design load of the intact structure is equal to damaged structure, R is defined as (Straub and Faber, 2005):

$$\boldsymbol{R} = \frac{\boldsymbol{V_{damaged}}}{\boldsymbol{V_{intact}}} \tag{2}$$

Where $V_{damaged}$ and V_{intact} are the base shear capacity of the damaged and intact structure, respectively, and R is the residual reserve strength ratio. R indicator is a number between zero and one. It is one when there is no capacity reduction in the damaged structure, and it is zero when the damaged structure has no capacity. More decrease in this factor indicates more reduction in structure capacity. The amount of R indicator was estimated in the target displacement for triangular and uniform lateral load distributions. The target displacement was calculated using the Equation 3-15 of FEMA365 (2000) recommendations.



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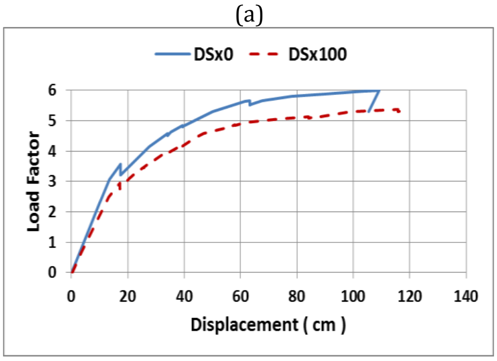

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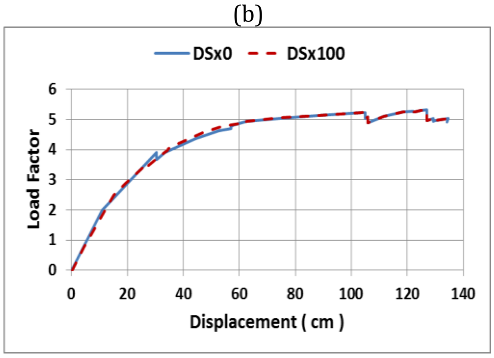

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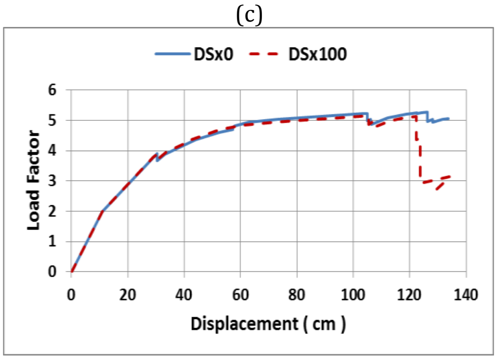


(d)

Fig. 7. Load factor-displacement relationship of DSx model for different lateral load patterns: (a) Triangular positive, (b) Triangular negative, (c) Uniform positive, (d) Uniform negative

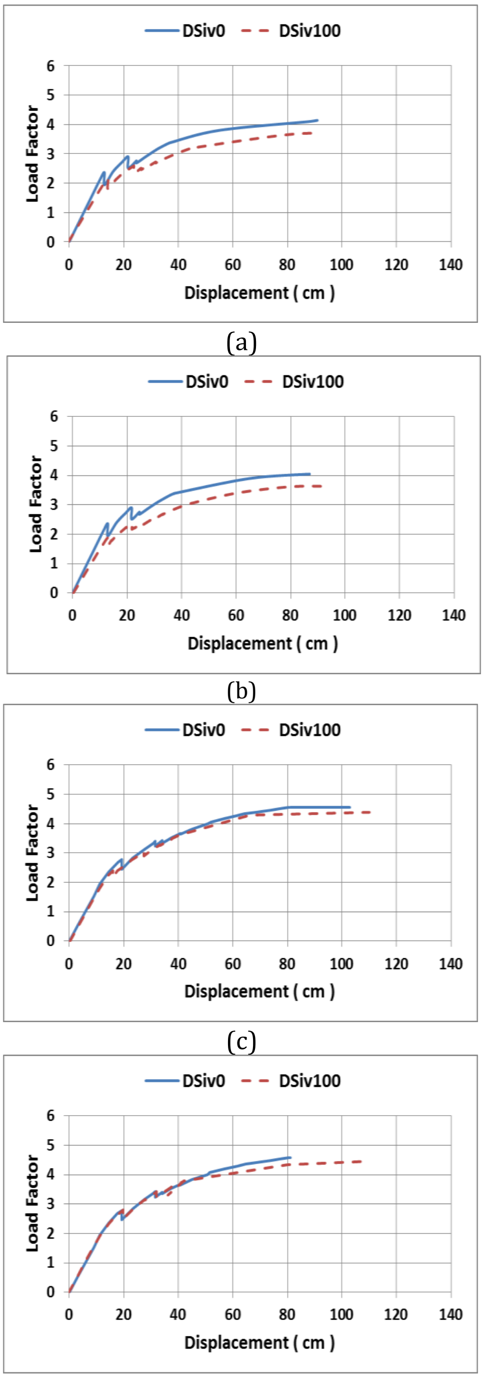


Fig. 8. Load factor-displacement relationship of DSiv model for different lateral load patterns: (a) Triangular positive, (b) Triangular negative, (c) Uniform positive, (d) Uniform negative

This ratio just shows the amount of seismic capacity reduction in target displacement, and it cannot compare to progressive collapse resistance, which does not calculate in a specific displacement. Table 5 shows the result of the *R* indicator for damaged structures.

According to Table 4, all models satisfied UFC acceptance criteria and have enough strength against seismic progressive collapse because their progressive collapse resistance is more than 1. Also, according to Table 5, R indicators are close to 1. This shows that capacity reduction in damaged models is negligible. Furthermore, models were checked for rehabilitation objectives which determine the relation of damage extent to a building (building performance level) to different earthquake hazard levels (FEMA356, 2000). It was found that all models satisfied life safety performance level for BSE-1 (10% in 50 years) earthquake as a limited rehabilitation objective that provides building performance less than the basic safety objective (BSO).

4.1. Effect of the lateral load distribution pattern

According to Fig. 7 and 8, the response of intact and damaged structures under uniform lateral load pattern was almost consistent. The most capacity reduction in damaged structures was seen in models under triangular patterns. According to Tables 4 and 5, the lowest amount of damaged structures resistance and *R* indicator is related to triangular patterns in the negative direction.

The first plastic hinge of the model structure under triangular patterns was formed in the brace of 2nd story. Afterwards, the model passed the UFC criteria by exceeding the allowed performance level of the aforementioned brace. In fact, concentrated formation of the plastic hinges in lower stories led to the most critical case. On the other side, the first plastic hinges of the model structure under uniform patterns were formed in the beams of the higher stories, and uniform distribution of plastic hinges led to the more appropriate performance of the structure. Therefore, the triangular load distribution pattern was determined as the more critical pattern due to more severe seismic impacts.

4.2. Effect of the brace configuration type

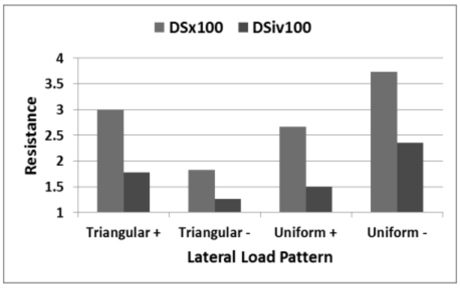
According to Fig. (9-a) and Table 4, DSx models had more progressive collapse resistance (and corresponding displacement) than DSiv models. For example, the progressive collapse resistance of DSx100 under the critical lateral load distribution pattern (negative triangular) was about 45% greater than DSiv100. Also, according to Fig. (9-b) and Table 5, the R indicator in the DSiv100 model was lower than the corresponding amounts in the DSx100 model. Therefore, structure with inverted V braces demonstrated more capacity reduction against seismic progressive collapse. In fact, the model with X braces had better performance against seismic progressive collapse than the model with inverted V braces because of more resistance, ductility and, residual reserve strength ratio, while previous studies (Kim et al., 2011) showed better performance of inverted V braces under gravity progressive collapse.

Table 4. Progressive collapse resistance of models under lateral loads

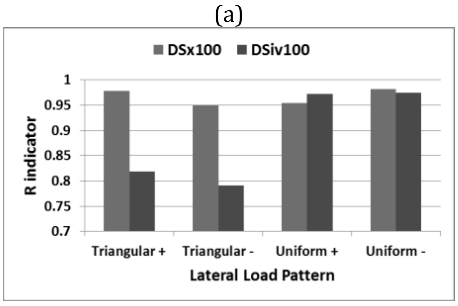
Model	Triangular positive		Triangular negative		Uniform positive		Uniform negative	
	Resistance	Dis. (cm)	Resistance	Dis. (cm)	Resistance	Dis (cm)	Resistance	Dis. (cm)
DSx0	3.036	17.0	3.040	17.0	3.865	29.8	3.860	29.8
DSx100	2.996	16.6	1.822	9.6	2.661	16.8	3.739	28.6
DSiv0	2.107	11.2	2.105	11.2	2.676	17.8	2.676	17.8
DSiv100	1.782	11.3	1.259	8.5	1.496	9.3	2.355	14.6

Table 5. R indicator of damaged models in target displacement under lateral loads

Model	Triangular Positive	Triangular Negative	Uniform Positive	Uniform Negative
DSx100	0.9785	0.9494	0.9539	0.9820
DSiv100	0.8187	0.7911	0.9719	0.9743



(a)



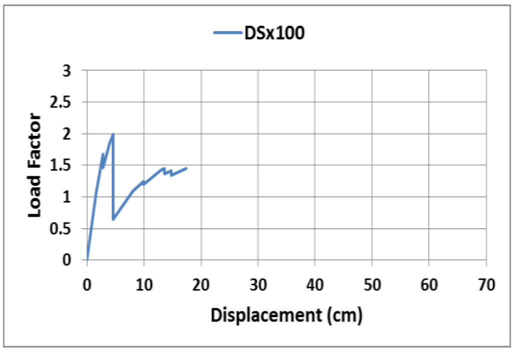
(b)

Fig. 9. Comparison of X and inverted V braces performance against seismic progressive collapse: (a) Progressive collapse resistance, (b) Residual reserve strength ratio

5. Comparison of structure performance under seismic and gravity progressive collapse

For comparison of the performance of damaged structures under seismic and gravity progressive collapse, pushdown analysis was carried out. The results were compared to the seismic progressive collapse resistance of DSx100 and DSiv100 under the critical lateral load pattern (negative triangular).

Load factor-displacement relationships for pushdown analyses are shown in Fig. 10, and Table 6 shows the results of the pushdown and pushover analyses (progressive collapse resistance and its corresponding displacement). As mentioned before in Section 4, the progressive collapse resistance of the structure is the maximum load factor satisfying UFC acceptance criteria. Also, corresponding displacement of pushover analyses related to the seismic progressive collapse resistance refers to the horizontal displacement of the mass center in the highest roof, and corresponding displacement of the gravity progressive collapse resistance in pushdown analyses defines as the vertical deformation of the point above the column removal location.



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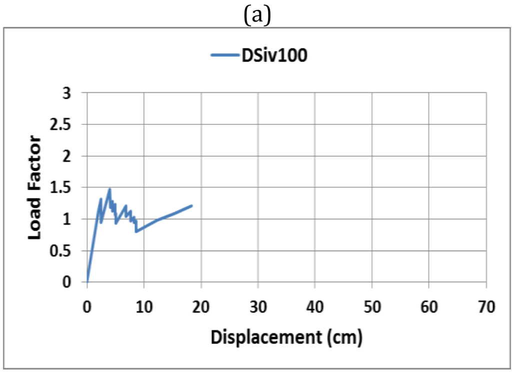


(b)

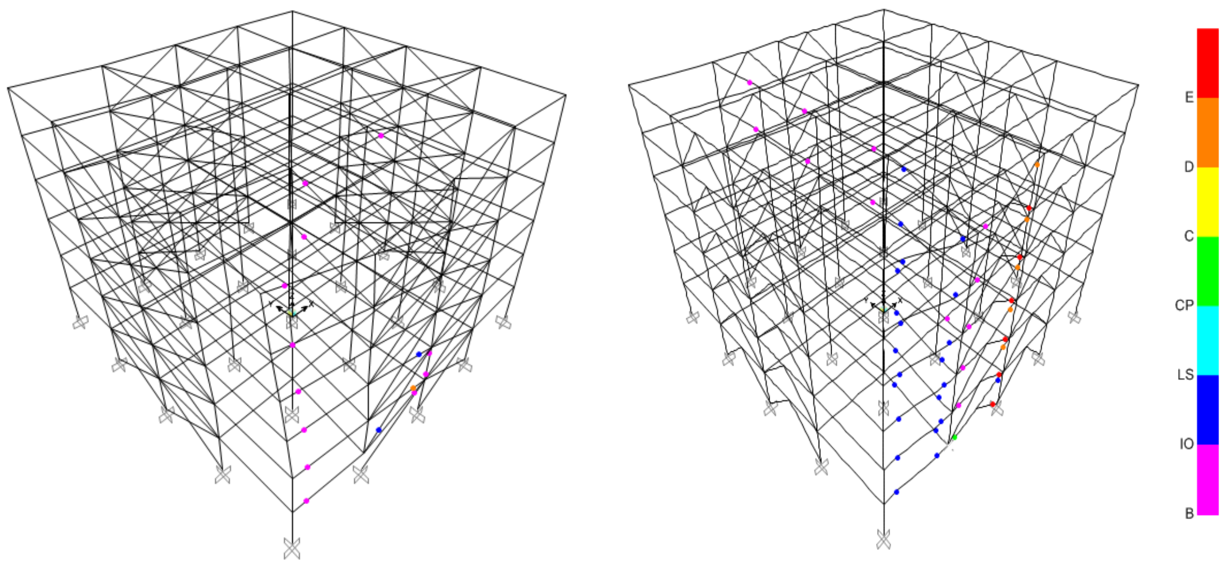
Fig. 10. Load factor-displacement relationship for damaged structures under gravity loads: (a) DSx100, (b) DSiv100

Table 6. Seismic and gravity progressive collapse resistance of damaged structures

Model	Gravity resistance	Dis. (cm)	Seismic resistance	Dis. (cm)
DSx100	1.111	1.6	1.822	9.6
DSiv100	1.069	1.9	1.259	8.5

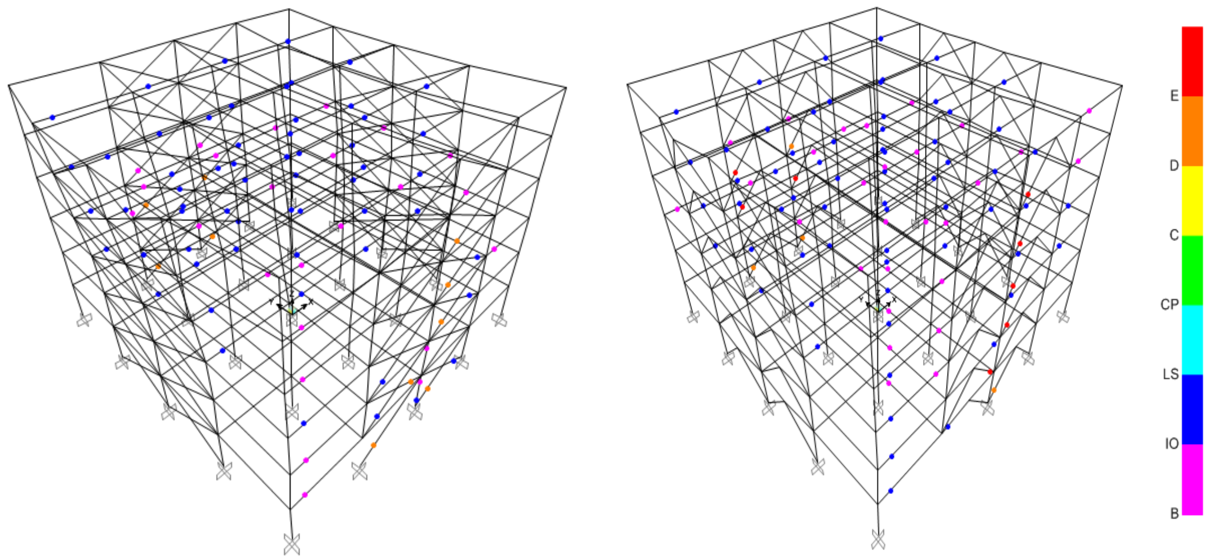
According to Table 6, structures possessed sufficient resistance (more than 1) to progressive collapse under gravity and seismic loads. Also, the seismic progressive collapse resistance of models was greater than gravity progressive collapse resistance. Progressive collapse resistance of DSx100 and DSiv100 under seismic loads was 64% and 18% greater than their resistance under gravity loads, respectively. Therefore, progressive collapse under gravity loads is more critical than seismic progressive collapse.

A comparison between pushdown and pushover analyses in Fig. (7-b), (8-b) and, Fig. 10 shows the ductile behavior of models under lateral loads and the brittle response of models under gravity loads. According to Table 6, models under seismic loads demonstrated more displacement than models under gravity loads. Corresponding displacement of gravity progressive collapse was about 1.5 to 2.0cm, while displacement in the seismic progressive collapse case was about 8.5 to 9.5cm. Therefore, the model structure under seismic loads shows 80 % more displacement capacity than the model structure under gravity loads. This proves the ductile and brittle behavior of models under seismic and gravity progressive collapse, respectively. To highlight the last point, the location of hinges for damaged structures under gravity and seismic loads after the collapse are shown in Fig. 11 and 12, respectively. According to Fig. 11, most of the hinges in structures under gravity loads were located close to the removed elements (B1 column and its adjacent brace) in the frame of elements removal. In fact, hinges formed in limited elements of damaged structures under gravity loads, while more hinges formed in the models under seismic loads distributed in entire of the structures. It means more elements participated in load redistribution of seismic progressive collapse. In fact, the nature of damage concentration in gravity progressive collapse leads to formation of limited hinges, whereas more hinges distributed in the model under seismic progressive collapse shows more ductility and redundancy.



(a) (b)

Fig. 11. Location of hinges under gravity loads in damaged structures after collapse: (a) DSx100, (b) DSiv100



(a) (b)

Fig. 12. Location of hinges under critical lateral load pattern in damaged structures after collapse: (a) DSx100, (b) DSiv100

Therefore, the structure under seismic progressive collapse had better performance than the structure under gravity progressive collapse because of more resistance, ductility, and redundancy.

6. Conclusions

In this study, the performance of dual systems with special steel moment-resisting frames and special concentric braces was compared under gravity and seismic progressive collapse, using the nonlinear static alternate path method recommended in the UFC (2016) guideline.

The parameters examined in this study were lateral load patterns and brace configuration types. The following important points can be stressed for studied models:

- All studied structures had enough seismic progressive collapse resistance. The model satisfied limited rehabilitation objectives. Therefore, seismic progressive collapse occurrence is not expected in dual systems with special steel moment-resisting frames and special concentric braces for one column and its adjacent brace loss scenario.
- The triangular pattern was critical lateral load distribution pattern in 6 story studied buildings experiencing seismic progressive collapse because of the lowest amount of damaged structures resistance and residual reserve strength ratio.
- The model with X braces had better performance against seismic progressive collapse than the model with inverted V braces for one column and its adjacent brace loss scenario because of more resistance, ductility and, residual reserve strength ratio.
- All studied structures under seismic progressive collapse had better performance than structures under gravity progressive collapse because of more resistance, ductility and, suitable load redistribution. In fact, more structural elements participated in load redistribution of seismic progressive collapse than gravity progressive collapse.

More studies are still needed to compare the seismic and gravity progressive collapses in the shorter or higher structures, considering different element loss scenarios, various bracing configuration or other structural systems. Also, more detailed model, for example including the wall and the floor slab, can be used in future studies.

References

American Concrete Institute (ACI 318), “Building code requirements for structural concrete”, Farmington Hills, Mich, 2005.

American Institute of Steel Construction (AISC 341), “Seismic provisions for structural steel buildings”, Chicago, US, 2016.

American Institute of Steel Construction (AISC 360), “Specifications for structural steel buildings”, Chicago, US, 2016.

American Society of Civil Engineers (ASCE 7), “Minimum design loads for buildings and other structures”, New York, US, 2005.

American Society of Civil Engineers (ASCE 7), “Minimum design loads for buildings and other structures”, New York, US, 2010.

American Society of Civil Engineers (ASCE 7), "Minimum design loads for buildings and other structures", New York, US, 2016.

Faroughi A, Moghadam AS, Hosseini M, "Seismic progressive collapse of MRF-EBF dual steel systems", Proceedings of the Institution of Civil Engineers-Structures and Buildings, 2017, 170 (1), 67-75.

Federal Emergency Management Agency (FEMA 356), "Pre standard and commentary for the seismic rehabilitation of buildings", Washington, D.C, 2000.

Fu F, "3-D nonlinear dynamic progressive collapse analysis of multi-storey steel composite frame buildings-parametric study", Engineering Structure, 2010, 32 (12), 3974-3980.

Fu F, "Response of a multi-storey steel composite building with concentric bracing under consecutive column removal scenarios", Journal of Constructional Steel Research, 2012, 70 (1), 115-126.

Galal MA, Bandyopadhyay M, Banik AK, "Vulnerability of three-dimensional semirigid composite frame subjected to progressive collapse", Journal of Performance of Constructed Facilities, 2019, 33 (3), 1-15.

General Services Administration (GSA), "Progressive Collapse Analysis and Design Guidelines for new federal office buildings and major modernization projects", Washington DC, US, 2003.

Ghobadi MS, Yakhchalian M, Yavari H, "Effects of torsional irregularity and seismicity level on progressive collapse potential of steel moment frames", Journal of Civil and Environmental Engineering, 2018, online published.

Guo L, Gao S, Fu F, "Structural performance of semi-rigid composite frame under column loss", Engineering Structures, 2015, 95 (1), 112-126.

Hosseini M, Fanaie N, Yousefi AM, "Studying the vulnerability of steel moment resistant frames subjected to progressive collapse", Indian Journal of Science and Technology, 2014, 7 (3), 335-342.

Khandelwal K, El-Tawil Sh, Sadek F, "Progressive collapse analysis of seismically designed steel braced frames", Journal of Constructional Steel Research, 2009, 65 (3), 699-708.

Kiakojouri F, De Biagi V, Chiaia B, Sheidaii MR, "Progressive collapse of framed building structures: Current knowledge and future prospects", Engineering Structures, 2020, 206, 110061.

Kiakojouri F, Sheidaii MR, De Biagi V, Chiaia B, "Progressive collapse assessment of steel moment-resisting frames using static-and dynamic-incremental analyses", Journal of Performance of Constructed Facilities, 2020, 34 (3), 04020025.

Kim J, Kim T, "Assessment of progressive collapse-resisting capacity of steel moment frames", Journal of Constructional Steel Research, 2009, 65 (1), 169-179.

Kim J, Lee Y, Choi H, "Progressive collapse resisting capacity of braced frames", Structural Design of Tall and Special Building, 2011, 20 (2), 257-270.

Kim J, Park J, "Design of special truss moment frames considering progressive collapse", International Journal of steel structures, 2014, 14 (2), 1-13.

Kordbagh B, Mohammadi M, "Influence of seismicity level and height of the building on progressive collapse resistance of steel frames", The Structural Design of Tall and Special Buildings, 2017, 26 (2), e1305.

Li S, Shan S, Zhai Ch, Xie L, "Experimental and numerical study on progressive collapse process of RC frames with full-height infill walls", Engineering Failure Analysis, 2016, 57, 57-68.

Mahmoudi M, Koozani H, Teimoori T, Hashemi SS, "Stability assessment of steel moment frames against progressive collapse", Journal of Civil and Environmental Engineering, 2016, 46 (1), 59-67.

Marjanishvili S, Agnew E, "Comparison of various procedures for progressive collapse analysis", Journal of Performance of Constructed Facilities, 2006, 20 (4), 365-374.

Musavi-Z M, Sheidaii, MR, "Effect of seismic resistance capacity of moment frames on progressive collapse response of concentrically braced dual systems", Asian Journal of Civil Engineering, 2021, 22 (1), 23-31.

National Institute of Standards and Technology (NIST), "Final Report on the Collapse of the World Trade Center Tower", Gaithersburg, 2008.

Park J, Kim J, "Fragility analysis of steel moment frames with various seismic connections subjected to sudden loss of a column", Engineering Structure, 2010, 32 (6), 1547-1555.

Rezvani FH, Asgarian B, "Effect of seismic design level on safety against progressive collapse of concentrically braced frames", Steel and Composite Structures, 2014, 16 (2), 135-156.

SAP2000, Structural Analysis Program, Computers and Structures, Berkeley, CA, 2004.

Shayanfar MA, Javidan MM, "Progressive collapse-resisting mechanisms and robustness of RC frame-shear wall structures", Journal of Performance of Constructed Facilities, 2017, 31 (5), 04017045.

Straub D, Faber MH, "Risk based acceptance criteria for joints subject to fatigue deterioration", Journal of Offshore Mechanics and Arctic Engineering, 2005, 127 (2), 150-157.

Suwondo R, Cunningham L, Gillie M, Bailey C, "Progressive collapse analysis of composite steel frames subject to fire following earthquake", Fire Safety Journal, 2019, 103, 49-58.

Tavakoli HR, Rashidi Alashti A, "Evaluation of progressive collapse potential of multi-story moment resisting steel frame buildings under lateral loading", Scientia Iranica, 2013, 20 (1), 77-86.

Unified Facilities Criteria (UFC), "Design of Buildings to Resist Progressive Collapse", Washington DC, US, 2005.

Unified Facilities Criteria (UFC), "Design of Buildings to Resist Progressive Collapse", Washington DC, US, 2016.

Wang J, Wang W, Qian X, "Progressive collapse simulation of the steel-concrete composite floor system considering ductile fracture of steel", Engineering Structures, 2019, 200, 1-18.

Wibowo H, Lau DT, "Seismic progressive collapse qualitative point of view", Civil Engineering Dimension, 2005, 11 (1), 8-14.

Yousefi AM, Hosseini M, Fanaie N, "Vulnerability assessment of progressive collapse of steel moment resistant frames", Trends in Applied Sciences Research, 2014, 9 (8), 450-460.