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Seismic Performance of Steel Buildings Connected by a Sky Bridge

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الملخص العربى:

يقدم البحث تقييما نظريا للسلوك الزلزالي للجسور التي تربط مبنيين معدنيين متجاورين من خلال التحليلات ثلاثية الأبعاد للعديد من النماذج الإنشائية. وفي حين تركز الدراسة على آثار الزلزال على القوى الداخلية المستحثة في الكمرات الرئيسية للجسر، يتناول البحث أيضًا آثار وجود الجسر على الأداء للمبنيين بشكل موجز. تم بناء وتحليل أكثر من 300 نموذج ثلاثي الأبعاد للمبنيين وجسر الأتصال باستخدام طريقة طيف التجاوب. وراعت هذه النماذج عوامل التحكم (التأثير) المختلفة مثل امتداد الجسر وارتفاعه وطريقة اتصال الجسر بالمبنيين؛ والصلابة النسبية للمبنيين؛ وكذلك اتجاه تأثير الحركة الأرضية الزلزالية بالنسبة لاتجاه محور الجسر. وأظهرت النتائج أن طريقة اتصال جسر الربط لها تأثير كبير على الاستجابة الديناميكية الشاملة للجسر في كل من الاتجاهين الموازى لمحور الجسر والعمودى عليه. كما بينت النتائج أن الجسر الرابط تأثر بشكل كبير بتغير جساءة المباني.

ABSTRACT

The seismic behavior of sky bridges linking two adjacent steel buildings is theoretically evaluated via numerous three-dimensional analyses. While the study focuses on the earthquake effects on internal forces induced in the bridge itself, the effects of the link presence on the global performance of the two buildings are also briefly addressed. Over 300 three-dimensional models of the building and connecting bridge are developed and analysed using the response spectrum method. These models consider various controlling parameters such as bridge span, elevation, and end conditions; relative stiffness of the two buildings; as well as direction of ground motion excitation with respect to bridge axis. Results showed that the connections of the linking bridge have a significant effect on the overall dynamic response of the bridge in both longitudinal and transverse directions. Also, the linking bridge itself was found to be significantly affected, with varying of the buildings stiffness and its direction of inertia.

Keywords: Connected Buildings; Sky-Bridge; Response Spectrum Analysis; 3D Model**;** Dynamic Response.

1. Introduction

Architects have shown interests in connecting nearby buildings as one or more specific levels to facilitate movements from one building to the other for function reasons. This is more frequently needed in high-rise buildings. One of the major advantages of sky bridges is increasing escape efficiency without adding more stairs in each building [Ronchi & Nilsson, 2014]. In many buildings, sky bridges are used at more than one floor according to architectural design. Naturally, these bridges are affected by the various loads that act on the bridge and buildings such as wind load, earthquake loads, and temperature variation. Carful design of these bridges is essential so that they could safely resist the internal forces resulting from such loads. This paper focuses on sky bridge design in various design scenarios.

Under dynamic loads such as earthquakes, the bridge and interconnecting buildings interact. This means that there is a mutual effect in which the bridge is affected by the movement of the two buildings. The bridge could also modify the dynamic properties of the system and affects their seismic response. Many studies were concerned with the seismic performance of sky-bridge-linked buildings and facilities. Tse et al. (2013) developed a 3-D analytical model of two linked towers and implemented it to investigate the modal properties of towers with multiple links. Lim et al. (2011) analyzed the structural coupling of twin buildings with a sky bridge. They derived the natural frequencies and mode shapes of the system with various relative stiffness of the sky bridge. Their results illustrated the dependence of the system natural frequencies and vibration modes on the stiffness of the sky bridge. Besides, the effect of the location of the sky bridge linking adjacent high-rise structures on the seismic response of both the structures and the sky bridge was explored by Mahmoud et al. 2016. They explored the dynamic performance of connected tall buildings with different characteristics under a suite of ground motion records. Besides, the effect of sky-bridge height on the induced dynamic responses of connected tall buildings was investigated by Mahmoud (2019) who considered seismic excitations in both longitudinal and transverse directions.

To complement already published work, this paper presents the results of an extensive parametric study conducted to evaluate the earthquake response of two buildings connected by a sky-bridge. The present study considers varying sky-bridge properties such as its length, elevation position, and boundary conditions at bridge-building connections; as well as variable stiffness ratios for the two buildings. It focuses on internal forces in the bridge and on base reactions of the connected buildings. Seismic excitations are applied once in direction of the bridge span, and then in the perpendicular direction.

2. Methodology

Linear response spectrum analyses are repeated to analysis the over 300 structure models of the two buildings and sky bridge systems. These structure systems are designed to comply with the relevant Egyptian codes of practice. In particular, the response spectrum used is based on ECP-201 (2012). The soil is assumed to be class C, and structure location is taken to be in Cairo. The response modification factor, R, is taken 5 as appropriate for steel frames with rigid connections.

2.1 Buildings and Bridge Description

The analyzed system is composed of two buildings, labeled A and B, connected by a sky bridge as shown in figure 1. This system is 100 m high (25 floors), and has a typical structural plan and a vertical plane of full symmetry. In all analyzed cases, building A is kept with the same plan size of 21×21 m and with the column and beam arrangement shown in fig. 1 (the floor is made of a reinforced concrete slab). However, plan dimensions of building B as well as the bridge elevation and span vary from one system to another. Steel sections for various elements are as listed in Table 1.

Table 1: Sections adopted for different structural elements

	Element Type	**Section Size**
Buildings	Column	Box 650×650×40
	Primary beams	HE 600A
	Secondary beams	IPE 400
	RC slab thickness (mm)	120
Sky Bridge	Primary beams	HE 600A
	Secondary beams	IPE 400
	RC slab thickness (mm)	120

2.2 Parameters

The parameters varied in this study are as follows:

(a) Plan dimensions of building B take one of five cases (x-length)×(y-length): 21×21, 63×21, 21×63, 105×21, and 21×105 in cases I, II, III, IV, and V, respectively.
(b) Sky bridge main beams connection to building B vary from hinged in x- and y-directions (case A); to hinged in y-direction but movable in x-direction (case B); to hinged in x-direction but movable in y-direction (case C); and finally to movable in x- and y-directions (case D).
(c) Bridge span length (S) varies as 10, 20, and 30 m.
(d) Bridge elevation (height above ground) is varied at fifth locations (i.e. h= 20, 40, 60, 80, and 100 m).

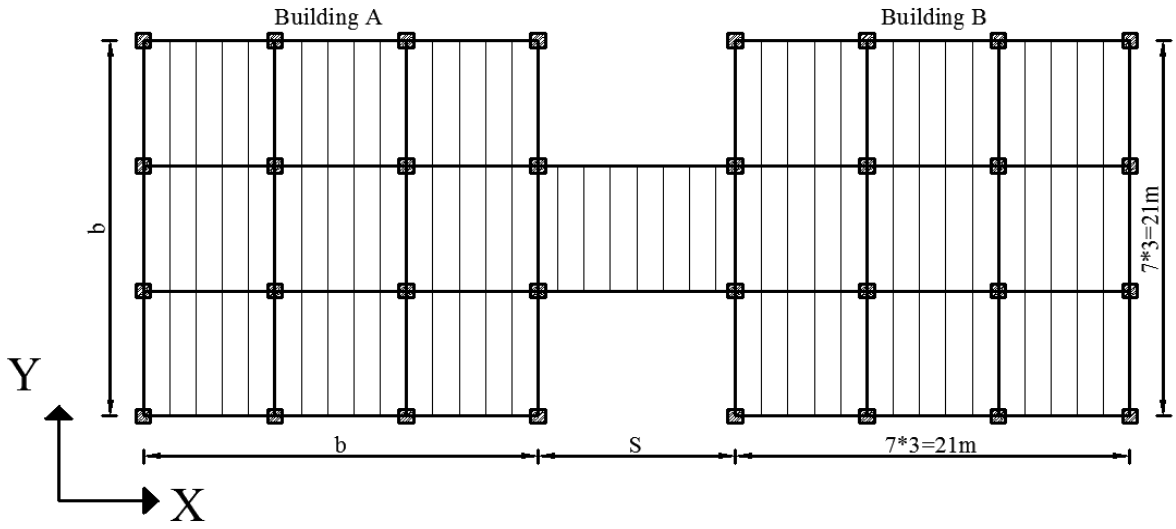


Figure 1: Plan of the structural model

3. Numerical results and discussion

For the sake of brief presentation, analyzed systems are coded as N –X – S – h, where N refers to the buildings' configuration (N= I, II, III, IV, or V); X refers to bridge end condition with building B (X= A, B, C, or D); S is bridge span; and h is bridge elevation.

3.1 Performance of sky bridge

In this section, the performance of the sky bridge due to seismic excitation of building-bridge system is investigated. This is done by analyzing the maximum horizontal shearing forces (MSF) and the maximum axial forces (MAF) produced in the main beams of the sky bridge.

3.1.1. Case of identical "twin" buildings

For the case of two identical buildings (i.e. both buildings A and B are with size 21×21), Tables 2 and 3 present the maximum axial and horizontal shearing forces in bridge main beams due to earthquake in x-, and y- directions, respectively. The forces are presented for various bridge span lengths and elevations as well as for different end conditions at Building B. For earthquake along the bridge span (x-direction), the horizontal shearing force is absent except for round off errors. Besides, axial forces are developed only due to inertia of the bridge mass where no interaction takes place between the two buildings. Therefore, the axial forces in bridge beams increase with the increase in bridge elevation (height), and in proportional to the bridge span length. When the bridge beams are restrained against x-translation at both ends (end condition cases A & C) the inertia force is equally divided between both ends. But, for end condition cases B & D where the beams are restrained against x-translation at one end only, the inertia force is carried by this end alone.

For earthquake in y-direction, the horizontal shearing force is developed due to inertia of the bridge. Hence, the shearing forces in bridge beams increase with the increase in either bridge elevation (height) or bridge span. When the bridge beams are restrained against y-translation at both ends (end condition cases A & B) the shearing force equals half the inertia force of bridge mass. However, for end condition cases C & D where the beams are restrained against y-translation at one end only, the shearing force becomes equal to the full inertia force. Axial forces develop in bridge beams due its bending in the horizontal plane. This bending transforms into equal tension and compression forces in the main beams. These axial tension and compression forces increase with bridge elevation up to level 80 m then decrease. For twin buildings, internal forces in bridge elements due to earthquakes perpendicular to bridge span are significantly higher than those caused by earthquakes parallel to the bridge span.

Table 2: Maximum axial and shearing forces in bridge main beams for the case of identical "twin" buildings subject to earthquake in x-direction (parallel to the bridge span).

Span	Height	Earthquake in x-direction							
		Axial Force(ton)				Shear Force(ton) Horizontal			
		A	B	C	D	A	B	C	D
10 m	20 m	0.18	0.36	0.18	0.36	0.01	0.01	0.01	0.02
	40 m	0.27	0.54	0.27	0.54	0.01	0.01	0.01	0.03
	60 m	0.33	0.66	0.33	0.66	0.01	0.02	0.01	0.04
	80 m	0.40	0.80	0.40	0.80	0.02	0.02	0.02	0.05
	100 m	0.46	0.91	0.46	0.91	0.01	0.01	0.10	0.04
20 m	20 m	0.38	0.76	0.38	0.76	0.09	0.01	0.01	0.03
	40 m	0.57	1.14	0.57	1.14	0.01	0.02	0.01	0.05
	60 m	0.69	1.38	0.69	1.38	0.02	0.02	0.02	0.06
	80 m	0.84	1.67	0.84	1.67	0.02	0.03	0.02	0.07
	100 m	0.96	1.91	0.96	1.91	0.01	0.02	0.01	0.06
30 m	20 m	0.57	1.16	0.57	1.16	0.01	0.02	0.01	0.04
	40 m	0.87	1.74	0.87	1.74	0.02	0.02	0.02	0.06
	60 m	1.05	2.10	1.05	2.10	0.02	0.03	0.02	0.07
	80 m	1.27	2.54	1.27	2.54	0.02	0.03	0.02	0.09
	100 m	1.46	2.91	1.46	2.91	0.02	0.03	0.02	0.09

3.1.2. Case of buildings with unequal size

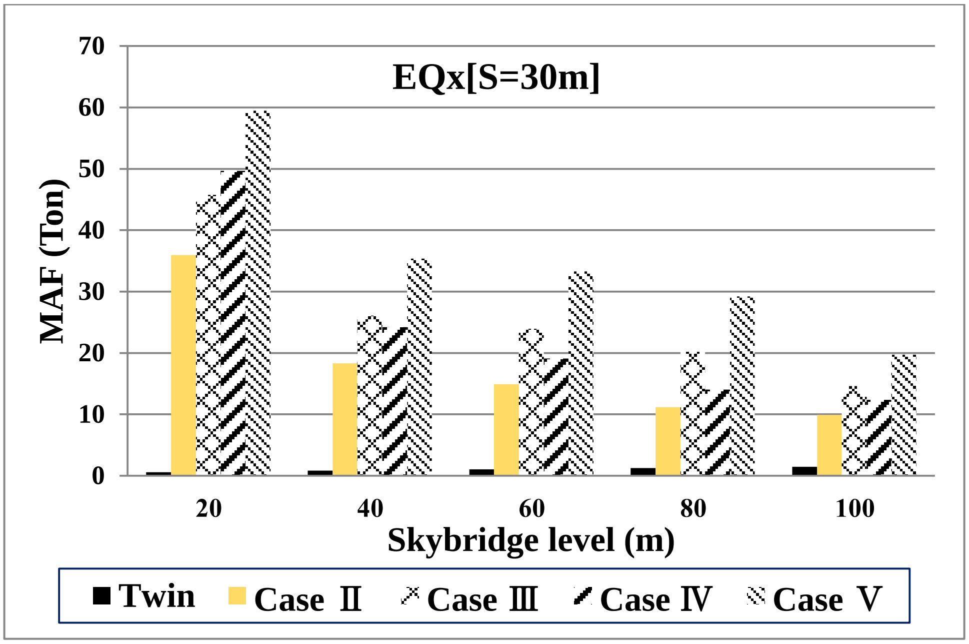
In this section, we present the internal forces in bridge beams for four cases depending on plan size of building B: 63×21, 21×63, 105×21, and 21×105 while building A is 21×21 in meters. These are labeled as cases II, III, IV, and V, respectively. The results are also compared to the case of twin buildings labeled as case I in which both A and B are 21×21. Different bridge levels, span lengths, and end conditions are considered and earthquake excitations is assumed in both x- and y- directions.

Table 3: Maximum axial and shearing forces in bridge main beams for the case of identical “twin” buildings subject to earthquake in y-direction (perpendicular to the bridge span).

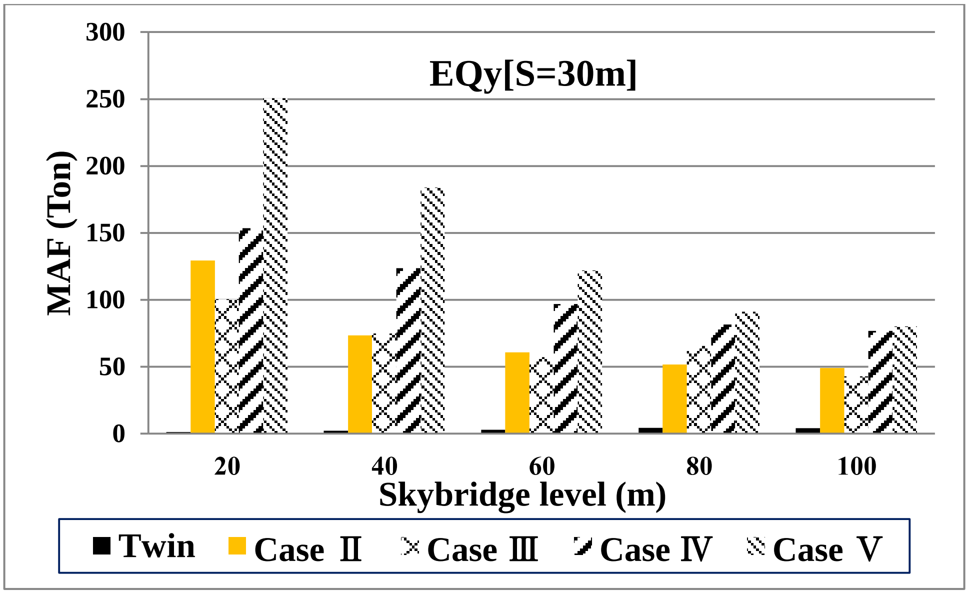
Span	Height	Earthquake in y-direction							
		Axial Force(ton)				Shear Force(ton) Horizontal			
		A	B	C	D	A	B	C	D
10 m	20 m	0.45	0.09	0.70	0.49	0.18	0.19	0.36	0.36
	40 m	0.75	0.13	1.10	0.75	0.27	0.28	0.55	0.55
	60 m	1.11	0.16	1.52	0.91	0.33	0.34	0.67	0.67
	80 m	1.46	0.19	1.97	1.11	0.40	0.42	0.81	0.82
	100 m	1.36	0.21	2.01	1.27	0.46	0.48	0.92	0.94
20 m	20 m	0.81	0.37	1.91	2.25	0.38	0.41	0.78	0.80
	40 m	1.46	0.55	3.09	3.37	0.57	0.62	1.17	1.20
	60 m	1.96	0.68	3.99	4.16	0.69	0.75	1.43	1.48
	80 m	3.17	0.82	5.31	5.16	0.84	0.91	1.74	1.82
	100 m	2.78	0.92	5.68	6.01	0.96	1.04	2.01	2.12
30 m	20 m	1.22	0.84	3.70	5.95	0.58	0.63	1.26	1.36
	40 m	2.13	1.28	5.95	8.52	0.87	0.96	1.86	1.97
	60 m	2.79	1.59	7.88	10.87	1.06	1.17	2.28	2.49
	80 m	4.31	1.93	10.16	14.11	1.27	1.43	2.82	3.19
	100 m	4.01	2.16	11.53	16.89	1.46	1.62	3.29	3.78

For bridge with a span length of S=30 m, and end condition type A (restrained in x- and y-translations), figures 2a and 2b present the maximum axial forces (MAF) induced in bridge main beams due to earthquakes in the x- and y- directions, respectively. In these figures, the results are shown for various building sizes (case I to V), and different bridge elevations. These results show that values of MAF induced by seismic excitation in case of buildings with unequal sizes are much more than that induced in case of identical buildings. Besides, it is noted that while the MAF increases with the increase in bridge elevation in case of identical buildings, the reverse takes place for building with unequal sizes. The important effects of bridge end connections with the buildings are also evident from figure 2.

Figure 3 shows the maximum shearing forces (MSF) in bridge beams due to earthquake in y-direction for the same conditions as considered in figure 2. Figures 2 and 3 show that- for sky bridges hinged in both buildings- the behavior of MSF is similar to that of MAF. Both building sizes and bridge elevation cause considerable changes in axial and shearing forces developing in bridge beams.



(a)



(b)

Figure 2: Maximum axial force in bridge beams for various bridge elevations and building sizes for case [N-A-30-h] due to earthquakes in direction: (a) x; and (b) y.

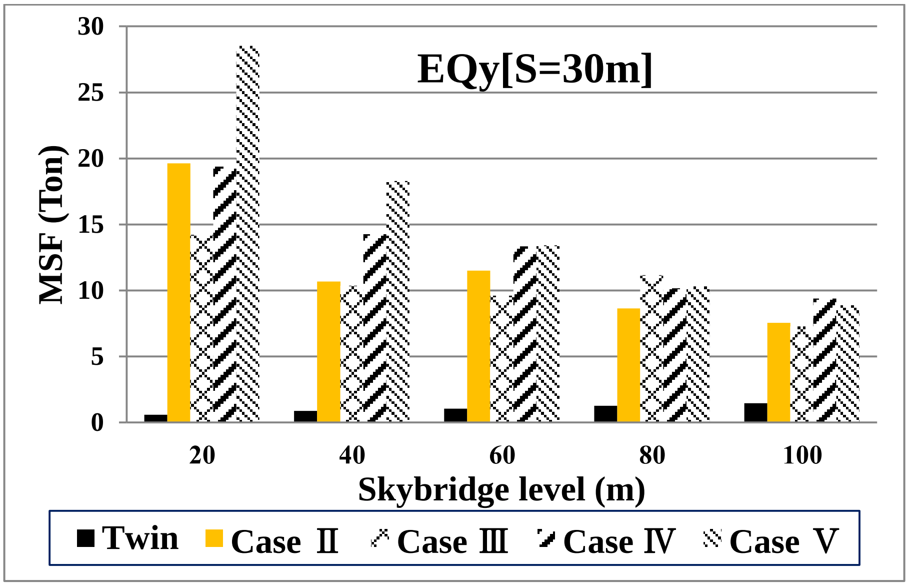


Figure 3: Maximum shearing force in bridge beams for various bridge elevations and building sizes for case [N-A-30-h] due to earthquake in y-direction.

Sample results are presented in figures 4 and 5 to highlight the effect of bridge end connection with buildings. Figures 4a and 4b present the MAF and MSF, respectively, produced in bridge main beams due to earthquakes in the y-direction for bridge with S=30 m, and end condition type B (restrained in y-translations only at tower B). Moreover, figures 5a and 5b depict the MAF produced by earthquakes in the x- and y- directions, respectively, for bridge with S=30 m, and end condition type C (restrained in x-translations only at tower B). Both figures show that the forces developed in bridge beams with partial release of horizontal translations (end connections types B & C) are greatly reduced to about 25% to 60% of the corresponding forces in case of full restrain of horizontal translations (end connection type A).

3.2 Performance of linked buildings

The effects of sky bridge presence on building performance are investigated. Thus, the impact of bridge on the seismic response of the buildings is studied in both horizontal directions. The investigated responses include top drift, base shear, overturning moment, seismic coefficient and level of seismic shear resultant. Results are presented for the cases of with bridge and are compared to those without bridge for different bridge and building configurations. The dynamic characteristics of individual buildings such as periods for translation and torsion vibration modes are also studied and compared with those of the connected buildings

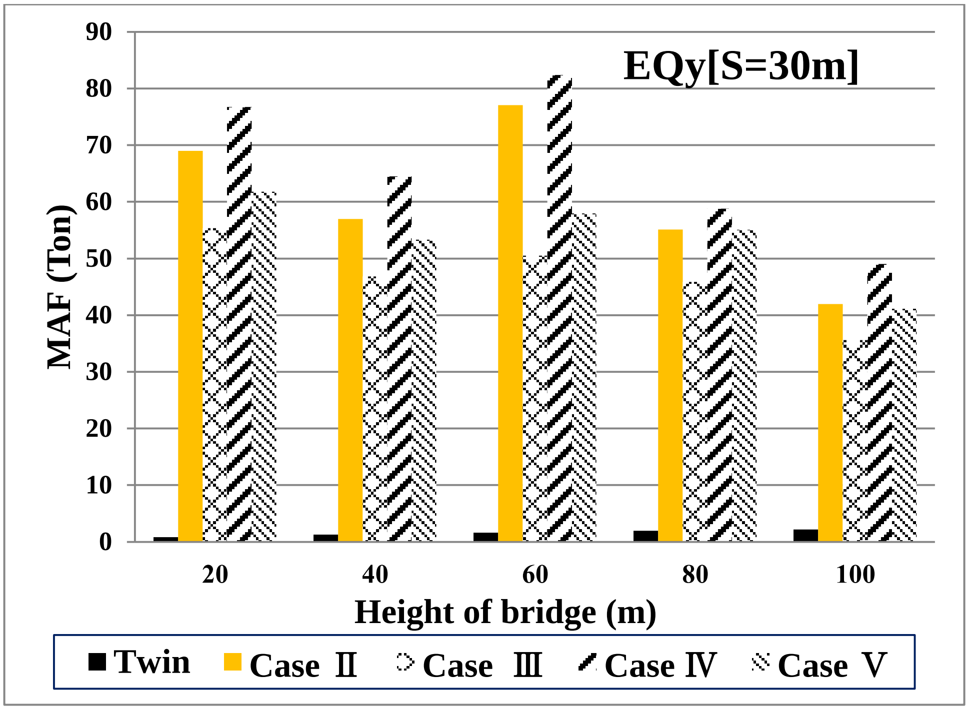
The seismic coefficient α is defined as the ratio between seismic base shear and seismic weight. Besides, the height of the seismic shear resultant is calculated by dividing the seismic overturning moment by the corresponding seismic base shear. Then, the coefficient of base shear resultant height ß is defined as the ratio of the height of seismic shear resultant to the height of the structure. Thus, α and ß are given as,

$$\alpha = V/W \qquad (1)$$

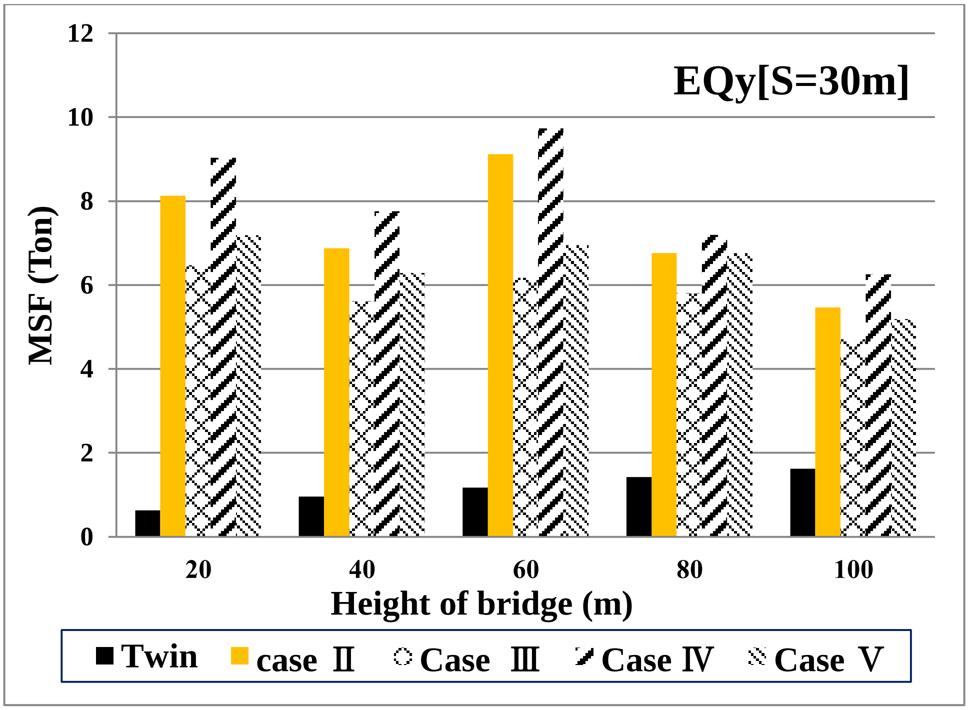
And

$$\beta = M/VH \quad (2)$$

Where α is the seismic coefficient, V is the seismic base shear, W is the seismic weight, ß is the base shear resultant height factor, M is the overturning moment, and H is the building height.

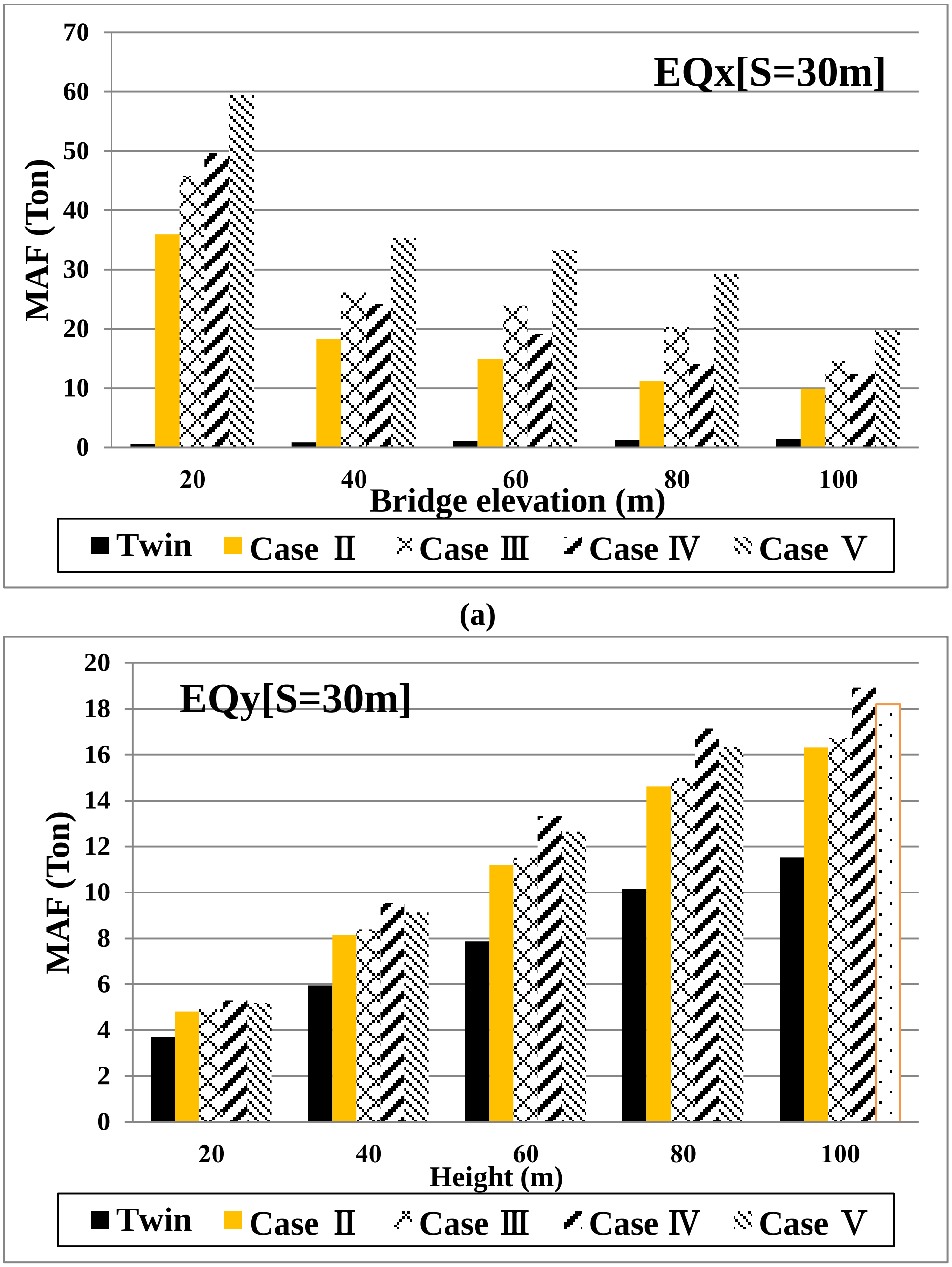


(a)



(b)

Figure 4: Maximum axial (a) and shearing (b) forces in bridge beams for various bridge elevations and building sizes; earthquake in y-direction, case [N-B-30-h].



(a)

(b)

Figure 5: Maximum axial force in bridge beams for various bridge elevations and building sizes for case [N-C-30-h] due to earthquakes in direction: (a) x; and (b) y.

The parameters used are steel bridge spans of 10 m and 30 m; bridge elevations of 20, 40, 60, 80, and 100 meter; two cases of the end conditions: Hinged-Hinged (A), and Hinged-Roller in both x and y-directions (D). Building systems Ⅰ, Ⅳ, and Ⅴ, seismic excitations in both x and y horizontal directions.

The results indicated that the change in the length and level of the bridge does not affect the first period for translation modes in both horizontal directions for connected buildings. Also, for dissimilar buildings, the translation first periods for cases IV and **V** were 10% more and 5% less than that of the square building in the weaker and stronger planes, respectively. Torsion modes for twin buildings are affected by -20% and +30% based on bridge span and elevation compared with individual square building.

The numerical values with variable bridge parameters showed no variations in the seismic coefficient, resultant height factor and total drift due to bridge presence for identical buildings compared with individual building as shown in Table 4. Table 5 shows results of *V*, *M*, *α*, and *ß* for building A, B and two building together when bridge end conditions are hinged (end connection type A) at S=30m for two cases IV & V. The values of *M* increase by increasing level of bridge for building B and decrease for building A. Values of α and ß approximately remain constant for all bridge parameters and building configurations.

Table 4: Results for seismic structural properties of buildings affected by ground motion in both x and y-directions

Case	**Building**	**EQ**	**V(Ton)**	**W(Ton)**	**M(Ton.m)**	**α**	**ß**	**Dx(m)**	**Dy(m)**
I	**A or B**	**EQx**	**304.4**	**11631.2**	**19619.96**	**0.0261**	**0.644**	**0.1902**	**0.2017**
		EQy	**304.6**	**11631.2**	**19631.37**	**0.0261**	**0.644**		
Ⅳ	**B**	**EQx**	**1511.6**	**56557.8**	**96406.52**	**0.0267**	**0.638**	**0.1665**	**-----**
V	**B**	**EQy**	**1510.9**	**56557.8**	**96393.21**	**0.0267**	**0.638**	**-----**	**0.1778**

Table 5: Results for seismic structural properties of buildings affected by ground motion in x and y-directions

Case	Height	V_A	M_A	α_A	β_A	V_B	M_B	α_B	β_B	V_T	M_T	α_T	β_T
Ⅳ	**20 m**	**295.9**	**22778.4**	**0.025**	**0.770**	**1499.7**	**92021.3**	**0.026**	**0.614**	**1795.6**	**114799.7**	**0.026**	**0.639**
	40 m	**293.2**	**20003.9**	**0.025**	**0.682**	**1520.6**	**95941.4**	**0.027**	**0.631**	**1813.8**	**115945.3**	**0.027**	**0.639**
	60 m	**289.7**	**18842.2**	**0.025**	**0.650**	**1526.9**	**97347**	**0.027**	**0.638**	**1816.7**	**116189.2**	**0.027**	**0.640**
	80 m	**285.9**	**18148**	**0.024**	**0.635**	**1531.4**	**98158**	**0.027**	**0.641**	**1817.3**	**116306**	**0.027**	**0.640**
	100 m	**284.2**	**17653.8**	**0.024**	**0.621**	**1533**	**98757.8**	**0.027**	**0.644**	**1817.2**	**116411.6**	**0.027**	**0.641**
V	**20 m**	**352.6**	**24657.9**	**0.030**	**0.699**	**1258.7**	**78312.4**	**0.022**	**0.622**	**1611.3**	**102970.3**	**0.024**	**0.639**

	40 m	**314.5**	**20995.**	**0.027**	**0.667**	**1400.6**	**88673.6**	**0.025**	**0.633**	**1715.2**	**109668.7**	**0.025**	**0.639**
	60 m	**291.2**	**18835.7**	**0.025**	**0.647**	**1442.1**	**92039.5**	**0.025**	**0.638**	**1733.4**	**110875.2**	**0.025**	**0.640**
	80 m	**281.6**	**17925.8**	**0.024**	**0.636**	**1452.9**	**93082.9**	**0.026**	**0.641**	**1734.5**	**111008.7**	**0.025**	**0.640**
	100 m	**278.7**	**17482.3**	**0.024**	**0.627**	**1454.7**	**93566.1**	**0.026**	**0.643**	**1733.5**	**111048.3**	**0.025**	**0.641**

4. Conclusions

The seismic performance of a structural system composed of a sky bridge linking two adjacent steel buildings is theoretically evaluated via an extensive parametric study. It is found that the seismic response of both the bridge and the two buildings are affected by variable parameters including: bridge span, elevation, and end conditions; relative sizes (mass and stiffness) of the two buildings; as well as direction of ground motion excitation with respect to bridge axis. The following are the specific conclusions drawn from analysis of obtained results; they are categorized into two sets to cover bridge response and building response.

For Bridge Response:

1. For twin buildings, internal forces in bridge elements due to earthquakes perpendicular to bridge span are significantly higher than those caused by earthquakes parallel to the bridge span.
2. Bridge end connections with the buildings have important effects on the bridges seismic forces. In particular, the forces developed in bridge beams with partial release of horizontal translations (along and perpendicular to bridge span) are greatly reduced to about 25% to 60% of the corresponding forces in case of full restrain of horizontal translations.
3. While the axial forces in bridge main beams increases with bridge elevation in case of identical buildings, the reverse takes place for buildings with unequal sizes. For instance, for twin buildings, the axial force in bridge main girders for bridge at elevation 100 m is about 2.50 times that of the bridge at elevation 20 m.

For building response:

1. For twin buildings, there is almost no change in the first periods for translation modes in both horizontal directions regardless of the bridge span or elevation. When the two buildings are dissimilar, the first periods for translation for the combined system are close to that of the stiffer building.
2. For a square building (b×b) connected to a rectangular one (b×5b) or (5b×b), the translation first periods of the rectangular building were 10% more and 5% less than that of the square building in the weaker and stronger planes, respectively.
3. Periods of torsion modes of the combined system are more sensitive to connecting bridge presence than periods of translational modes.
4. For buildings with similar characteristics (identical buildings), the seismic response as described by the seismic coefficient α, the resultant height coefficient ß, and the

overall drift is the same for the two cases of with and without sky bridge. This observation is valid for all scenarios of bridge to buildings' connections. Negligible variations are observed in the response due to presence of bridge mass and its relative position. In reality, the response would be a little different as buildings cannot be 100% identical as is theoretically assumed in the study. Response variations of similar building in practice may result from dissimilarities in occupation, soil, or other conditions.

5. When the sky bridge is hinged (in XZ and YZ planes) to one building, but is roller-supported (in XZ and YZ planes) on the other building, buildings' response is not coupled. However drift of the building to which the bridge is hinged increases due to bridge mass particularly for large bridge spans. This remark is correct for similar and dissimilar buildings.
6. When the sky bridge is hinged (in XZ and YZ planes) to two dissimilar buildings, the seismic responses of the two buildings become coupled. The following remarks describe the effect of this coupling:
   - The seismic coefficient is reduced by up to 20% of the single building response in the softer building. This reduction is more pronounced for bridges located at higher levels, for bridges with larger spans, and when the ratio between the lateral stiffness of the two connected buildings is large.
   - Besides, bridge presence produce an upward shift in elevation of seismic resultant force acting on the softer building by more than 20% of its elevation in the single building response. This shift is observed when the bridge is at lower levels while a reverse behavior (i.e. downward shift) occurs for bridge at higher levels. In both cases, the shift increases as the ratio of buildings' lateral stiffness increases.

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