RESEARCH ARTICLE

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Improving the Overall Buckling Resistance of the Chevron Braced Steel Frames using Lintel Band

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Abstract

In this article the capability of steel lintel bands in steel frames has been scrutinised for the improvement in the overall buckling strength/resistance. By adding the lintel bands to the Chevron braces frames, Chevron braces were got upgraded for an improved buckling resistance. Modified Chevron bracing arrangement also improved the buckling resistance of the weak-beam and strong-column frames significantly. For comparison, X braces were analysed. X braces were found to be a constrained option with various limitations (*including the size of the braces in combination with the size of the beams*). Lintel bands were found to be consistent and work well in all the considered cases including the frame configurations in which X brace failed to fulfil the purpose. The buckling behaviour of eccentrically and concentrically Chevron braced frames was studied by including lintel bands and lintels at the general lintel location. Through this article, it has been conveyed that the lintel bands can be used as a good companion of the braces and can be included in the Chevron braced frames to improve its buckling behaviour under both the lateral/ horizontal and the vertical loads.

Keywords: Steel frame, Lintel, Lintel band, Brace, Buckling.

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Introduction

Many researchers have used braces to improve the seismic response (to absorb energy and to reduce hysteresis losses etc.) of the buildings/ structures. '*Lintels*' are basically used to bear the wall load above the openings and to transfer the load in the infill walls of framed structures and in the load bearing walls of the masonry structures. '*Lintel bands*' are generally used in the form of steel straps around the masonry buildings or as the lintels extended to the edges to the load bearing walls or between columns of RCC framed structures to improve lateral load capacity to counter the induced seismic forces. In this analytical study, the effect of the inclusion of lintel bands as struts between columns and the lintels as struts between the eccentric/concentric chevron braces, on the buckling behaviour of steel frames has been studied and compared with other type of bracing. Concepts of buckling have been well explained in the books [1]-[3]. Major component of storey drift in Moment resisting frames (MRFs) is contributed by the rotation of the floor beams, and to achieve the desired drift limitation, the size of beam has to be increased or the braces are to be used [4]. The MRFs have minimum stiffness and CBFs (concentrically braced frames) have the maximum stiffness [5].

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After a brace had buckled, the unbalanced forces in the beam can lead to soft storeys in the multi-storeyed frames [6]. Gengshu *et al* introduced the concept of threshold stiffness and explained criteria for identifying a weakly braced frame [7]. Sabelli *et al* used numerical modelling to predict the brace demands [8]. In the masonry buildings, the twin lintel belt and vertical corner reinforcement resist lateral load better than conventional stitching repair [9]. Sarno *et al* designed a 9-storey moment resisting steel frame (MRF) and analysed it for improved performance under earthquake ground motions by retrofitting it using three bracing configurations separately [10]. Unlike generally used RCC ring beams (Horizontal band), Borri *et al* used composite reinforced masonry ring beams in masonry structure to improve lateral load resistance under seismic forces [11]. Tasnimi *et al* investigated the in-plane seismic behaviour of steel frames with brick masonry infill having central openings in it. Formation of cracks along the strong spandrel beam resulting in higher frictional hysteretic damping was found to be partially depended on the lintel beam [12]. In the numerical analysis of progressive collapse situation (internal columns removed), the braced frames worked better than the moment resisting frames [13]

Lignos *et al* conducted loading experiments for prediction of the side-sway collapse of steel moment frames and found that the commonly used symmetric cyclic loading histories provide insufficient information for modelling the deterioration near collapse [14]. Eghtesadi *et al* selected various framed structures for analysis and found that the X-brace have only one lateral force resisting member in each span, so require stronger beams and columns [15]. The provisions of strengthening measures like lintel bands and steel reinforcements around the openings of the infill panels restrict the reduction of stiffness and strength under seismic loading [16]. Gerasimidis generated progressive-collapse mechanism by removing the key element of the structure. It was found that, when the removal of column happens at the bottom stories, buckling of column governs the collapse mechanism and when the removal of column happens at the upper stories, collapse mechanism is governed by the flexural failure of beams [17]. Choudhury *et al* found that Steel bands in masonry buildings improve its lateral load carrying capacity [18]. Dutta *et al* suggested retrofitting in a RCC framed structures by filling the empty corner bays with brick masonry and by providing lintel beams in open bays to avoid soft story of bottom storey [19]. In the investigation of the effect of the distributed and the concentrated lateral loading, through the experimental and the analytical study on a single storied masonry in-filled steel framed structure, it was found that the formulas, mostly based on the specimens with concentrated loading only, were conservative [20].

In this study, Chevron braced frames have been selected for upgrading with the inclusion of lintel bands. The lintel bands can be included in the new chevron braced frames and can be also added to the existing chevron braced frames. Similar strategy showed good plastic dissipation and hysteretic characteristics for an old Chevron braced steel frame [21]. The horizontal lintel bands (*ties in case of the masonry structures and in-filled framed structures*) have been used in earthquake resistant structures to improve the seismic performance of the structure and resist sway. In this numerical study, steel lintel bands have been examined for their capability to resist buckling in combination with the Chevron braces.

METHODOLOGY

Linear perturbation buckling analysis was conducted for the rigidly connected steel portal frames ranging from single storied frame to 5 storied frames. Initial analyses of the frames were done by introducing rigidly connected lintel bands to check for the improvement in the overall buckling resistance of the structure. The results were compared with the frames having rigidly connected conventional cross-bracings. Then the analyses were done by including lintel bands with the chevron braces. The radius of the columns sections was kept constant as 50 mm, the radius of the beams was varied from 50 mm to 30 mm and radius of the braces/ lintel bands was varied from the radius equal to the radius of the beam to 30 mm. The height of each storey was considered as 3m and the position of lintel band was kept as 2m to accommodate door and considering the improvement in the critical load. Link length of the eccentric brace was taken as 1m, which avails open area and improved buckling behaviour.

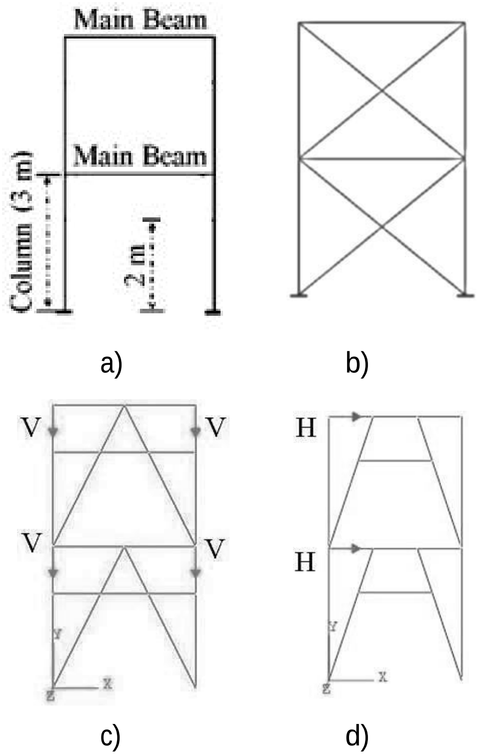


Figure1: a) One bay two storied frame with lintel bands, b) X bracing, c) Vertical loading in Chevron braced frame with lintel bands and d) Lateral loading in eccentric Chevron braced frame with lintels. Nomenclature is given in notes below

Notes:

i) *Nomenclature:* **H** reresents lateral/ horizontal load (where, **H0** is for the bare frame case), **V** represents vertical load (where, **V0** is for the bare frame case), **LB** represents lintel band, **X** represents cross brace, **Ch** represents chevron brace, **c** represents concentric, **e** represents eccentric, **Bm** represents beam, **St** represents lintel/ strut, ***Pcr*** represents critical Load, **Br** represents brace and **r** represents radius.

ii) *Frame configurations:* B1S**n** represents a frame having 1 bay (**B1**) and '**n**' number of stories, '**S**'. For defining the frame elements radii in tables and bar charts, **a, b (c/e), d** representation has been used. Where, '**a**' represents beam radius, '**b**' represents brace radius, '**d**' represents lintel band or strut/lintel radius and (**c/e**) represents either concentric or ecentric case of Chevron brace. All cases considered above were analysed for **B1S1**, **B1S2** and **B1S5** configurations of the steel frames.

iii) *Cases considered*: a) bare frame, b) frame having either lintel bands (**LB**) or the braces (**X** brace or **Ch**evron brace (**c**oncentric/ **e**ccentric), c) frames having Chevron braces (concentric/ eccentric) and lintel bands (**Ch(c/e)+LB**) and d) Frames having Chevron braces (concentric/ eccentric) with lintel bands in upper/lower stories and X braces in lower/upper stories ((**Ch(c/e)+LB), X**).

Result and Discussion

The results of buckling analysis are basically the critical loads values (*Pcr*), for uniform horizontal and vertical loadings. The cross-sectional radius of the column has been kept as 5 cm in all the analyses. The critical loads for the bare frames are given in Table-1. All values in other tables and graphs are in the ratio of these values.

Table-1: Critical Load Values of the Bare Frames

Beam radius	B1S1		B1S2		B1S5	
(cm)	H0 (MN)	V0 (MN)	H0 (MN)	V0 (MN)	H0 (MN)	V0 (MN)
5	3.34	0.80	1.39	0.38	0.23	0.13
4	2.09	0.61	1.16	0.26	0.19	0.08
3	0.95	0.41	0.76	0.14	0.18	0.04

Lintel Banded Frames and X Braced Frames

In Table-2, **(Annexure-1)** for single bay and single story frame, it can be seen that the lintel band of all considered size work well for all sizes of beams. Bare frames have been considered as the references in the table. Looking at the improvement in critical load by braces, they were found to work better than lintel bands against vertical loads but their drawback was that event-though they increased buckling resistance against vertical loads, they failed to even reach the horizontal critical load achieved by the bare frame in many cases.

In all the analyses with lintel bands, the improvement in buckling load was more significant in the case of higher size of beams with higher size of lintel band. For 3 cm size beam and lintel band, the improvement was not significant in comparison to 5 cm size beam and 5 cm size lintel band as the critical load increased almost twice in comparison to the 5 cm radius beam with no lintel band. In case of both the lintel bands and braces, same size of beam and lintel/braces showed better results, even better than some cases of higher size of beams.

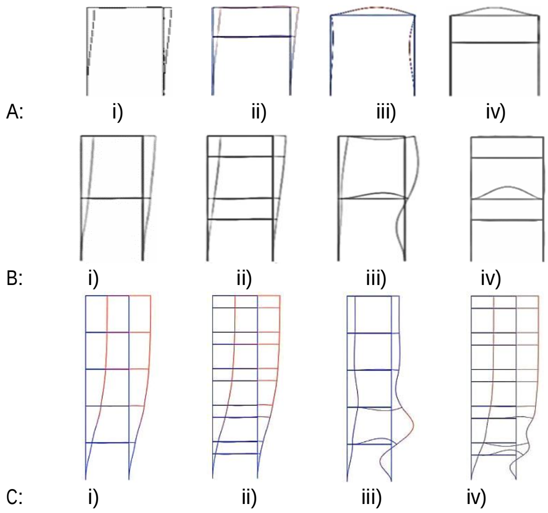


Figure 2: Changes in buckling modes on introduction of Lintel band. A) B1S1 frame, B) B1S2 frame, C) B1S5 frame. Whereas, sub-divisions represents, i) V0, ii) V with LB, iii) H0, iv) H with LB

Figure 2 shows the changes in buckling modes of frame on the introduction of the lintel bands in it. The straight members represent the original state and the deformed shape shows the first buckling mode. In this figure, weak beam-strong column cases have been shown, where the size of columns is 5 cm and the size of the beam and the lintels is 4 cm. The modified configuration showed an improved buckling behaviour (See Table-2). The introduction of lintel band had minor benefits under vertical loading but it significantly restrained the buckling of the columns under lateral loading (See Figure 2).

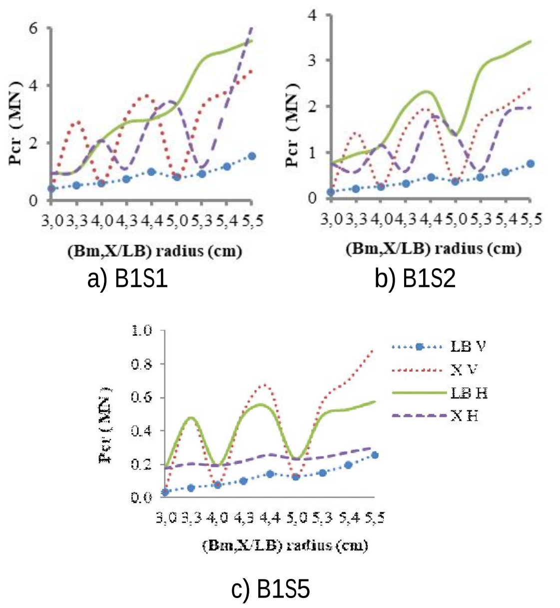


Figure 3: Critical load values trend for the selected configurations

As the number of stories rose, the effect of bracing configuration in controlling buckling diminished rapidly under lateral loading whereas the effect of lintel band had a consistent nature for all the considered stories (See Figure 3). Under vertical loading braces performed much better than the lintel bands and the trend shown in Figure 3 justified their efficiency under vertical load. This can also be observed that with the increase in number of stories, the trend of critical load values under lateral loading with the lintel band followed the trend of bracing configuration under vertical loading. This shows a huge improvement in lateral buckling load capacity of the frames on introduction of lintel bands in comparison to bracing configuration.

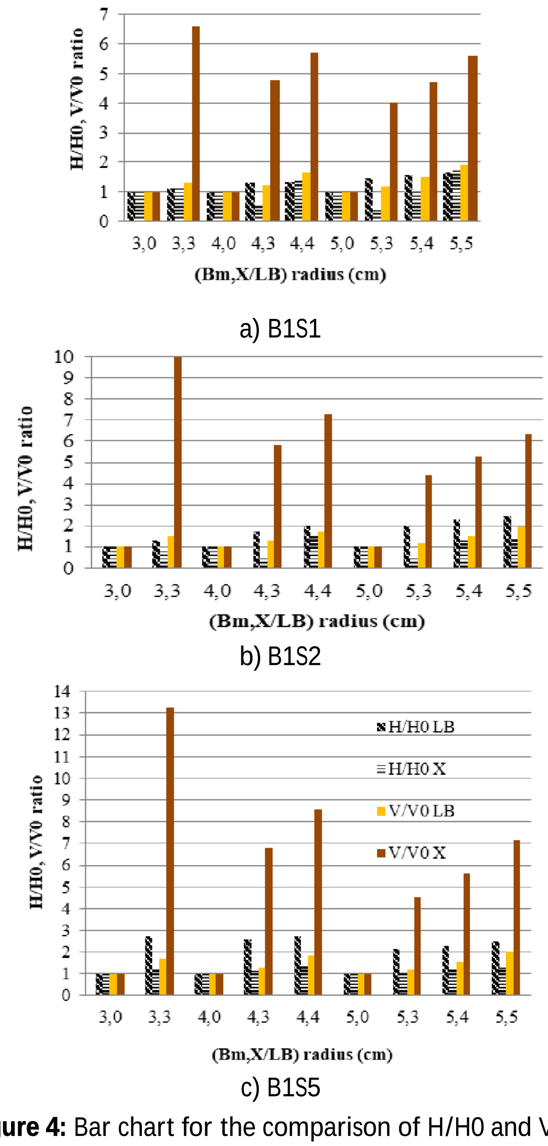
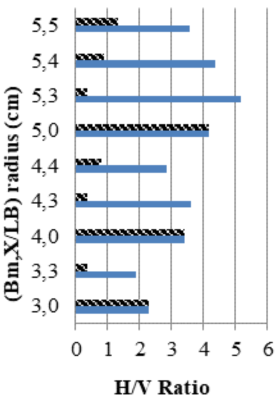
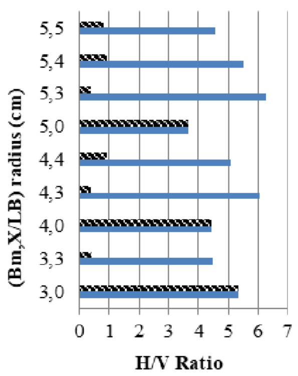


Figure 4: Bar chart for the comparison of H/H0 and V/V0 ratio including lintel bands or the cross braces in the steel frames

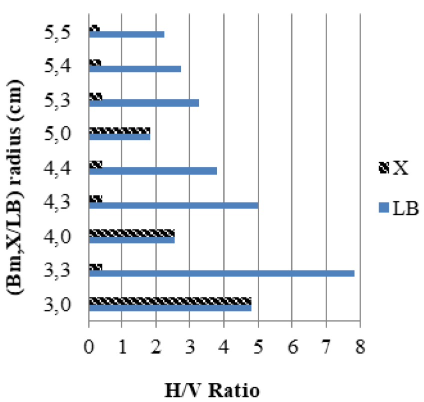
For the comparison of ratio of horizontal and vertical critical loads of bare frame, lintel banded frame and braced frame, in Figure 4. H/H0 is the ratio of horizontal critical load of the braced/lintel banded frame to the horizontal critical load of the bare frame having same beam size. Similarly, V/V0 is the ratio for the vertical critical load. Bare frame cases have been used for the reference. Through the bar chart it can be seen that the improvement was there in V/V0 ratio in all the considered cases. Even-though for the braced frames this ratio was much higher than the lintel banded frame but the ratio is greater than 1 in all the cases of lintel banded frame and the braced frame. Whereas, this was not the situation in case of H/H0 ratio as in two cases of B1S1 frame configuration, the H/H0 ratio for braced frame was less than 1 and in three cases of B1S2 frame configuration, the H/H0 ratio for braced frame was less than 1.



a) B1S1



b) B1S2



c) B1S5

Figure 5: Bar chart for the comparison of H/V ratio including lintel bands or the cross braces in the steel frames

Comparing the change in the ratio of horizontal critical load to the vertical critical load of a considered frame, represented by H/V, it can be clearly observed from Figure 5, that the braced frames were found to alter this ratio to a very large degree in comparison to its corresponding bare frame condition. H/V ratio of the braced frame is very less in comparison to the bare frame condition but the lintel banded frames haven't altered this ratio for the frames much.

Chevron Braced Frames

From the bar chart (see Figure 6), it can be seen that H/V values in the bare frame condition were very much higher than the ratio of the values in the Chevron braced frame condition for any of the storey heights. Even-though H/V ratio didn't gave any idea about the improvement in the critical load values, it did represented the change of the behaviour of the frame under vertical and horizontal loading. Under various loadings, the behaviour of the frame changed very much after its bracing in comparison to bare frame condition.

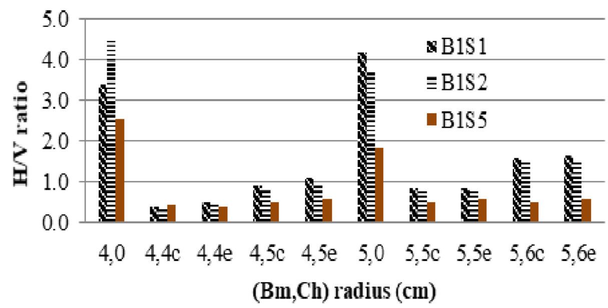
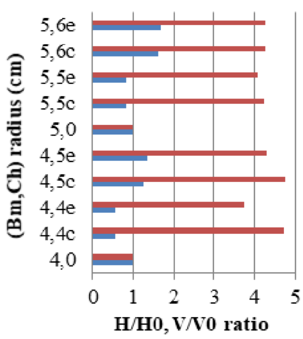
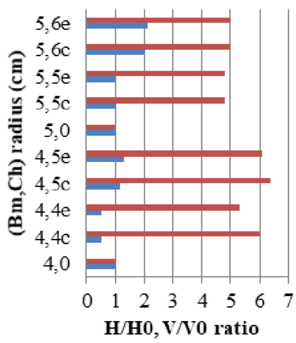


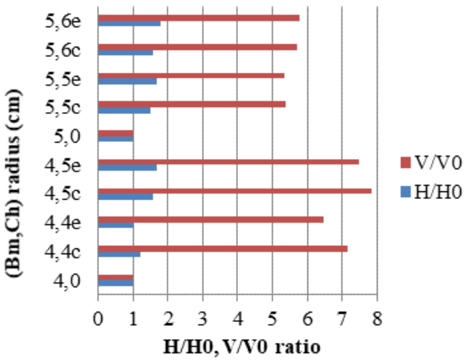
Figure 6: Bar chart of H/V ratio of Chevron braces in the steel frames



a) B1S1



b) B1S2



c) B1S5

Figure 7: Bar chart of H/H0 and V/V0 ratio including Chevron braces in the steel frames.

In all the cases of Chevron braced frames value of V/V0 was higher than 1, which showed the improvement in critical load under vertical loading (see Figure 7). Even-though there was ample rise in critical load value under vertical load on inclusion of Chevron braces but in four of the considered cases of B1S1 configuration and in two cases of the B1S2 configuration, H/H0 values were less than 1.This showed the serious reduction in the critical buckling load value under horizontal loading on inclusion of Chevron braces of the considered cross-sections with different size of the beams.

Chevron Braced Frames with Struts or the Lintel Bands

It can be observed from the Table-3 **(Annexure-2)** that in all the considered cases, on the inclusion of the lintel bands in the Chevron braced frames, there was an increase in critical load value under vertical load represented by V/V0 ratio. Column radius has been kept fixed as 5 cm throughout the analysis. For weak beam - strong column, having beams of 4 cm radius, including lintel bands of 4 cm, there was ample rise in H/H0 ratio. This shows the capability of this combination to satisfy the ductile detailing criteria and strength criteria, which was not possible with Chevron braced frames alone. It can also be seen from Table.2 that the '*lintel bands*' (LB) were found to work better than '*lintels/struts*' (St) for most of the frame configurations.

Modified bracing with a conventional bracing type at different stories

By combining two type of bracing in a frame (at different levels/stories), frames were examined for the improvement in the collapse characteristics of the multi-storied frame. It can be deducted from the results that X brace worked better than Chevron brace under both vertical and lateral loading in most of the cases. So, with the new bracing arrangement (Chevron with lintel band), X brace were selected as the conventional brace for combination in different stories. B1S5 frame configuration has been considered for combination of braces. Beam radius was varied from 5 cm to 4 cm. Brace radius varied from 5 cm to 4 cm. All the braces had same cross-section, irrespective of their type.

Some cases were discussed lightly and the significant cases were presented in detail. In all the frames, braced throughout with same type of conventional braces, buckling was observed in the ground storey itself. Including only the lintel bands at the lower stories and X braces at upper stories was not found to be acceptable because of the soft-storey reason and also according to buckling consideration as buckling occurred at the lowest stories under both vertical and lateral loadings. Neither was it found to be appropriate to include only the lintels at upper stories and X braces under lower stories as under lateral loading buckling occurred at lower stories and under vertical loading buckling with excessive deflection (like the bottom fixed and other end free buckling of a bar) started from the lowest lintel banded storey. Also, placing X braces at the bottom stories with either of the eccentric or concentric modified Chevron braced cases (with lintel bands) at upper stories was found to be non-workable as buckling occurred at the bottom storey under both vertical and lateral loadings.

The combination of braces having modified Chevron braces at bottom stories was found to be workable; as in many cases, the buckling was observed in upper stories rather than starting with the bottom storey.

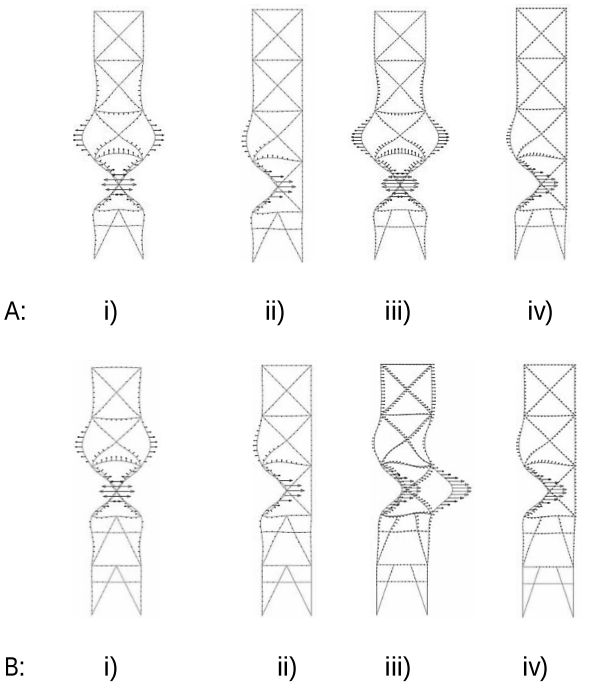


Figure 8: Case 1(A, B) of Table.4. i) and ii) have Ch(c)+LN; iii) and iv) have Ch(e)+LN. Modal displacements are shown by arrows.

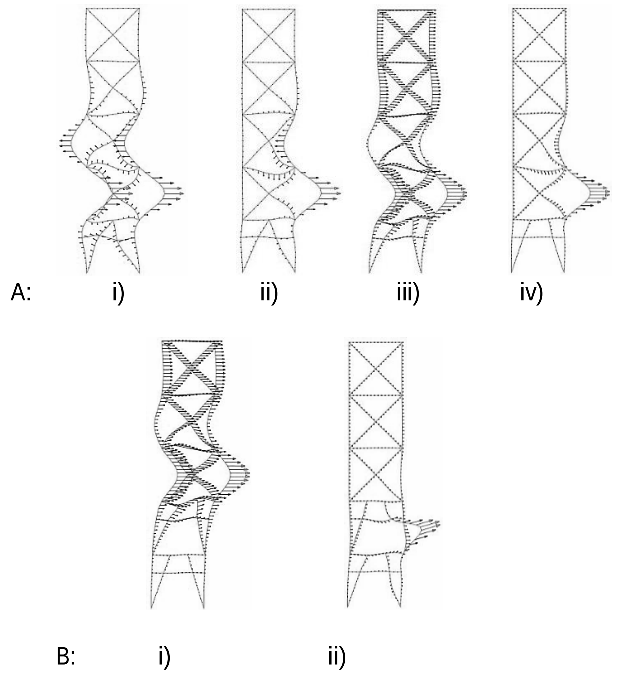
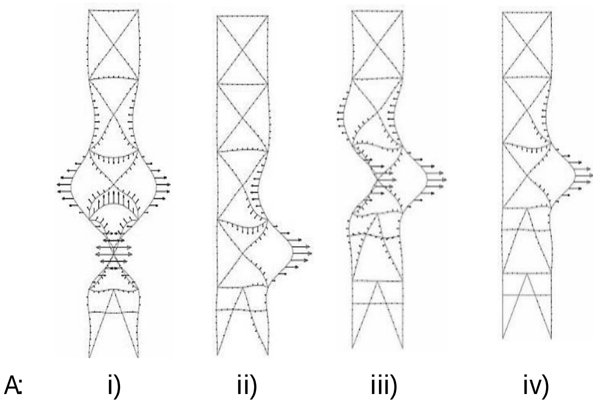


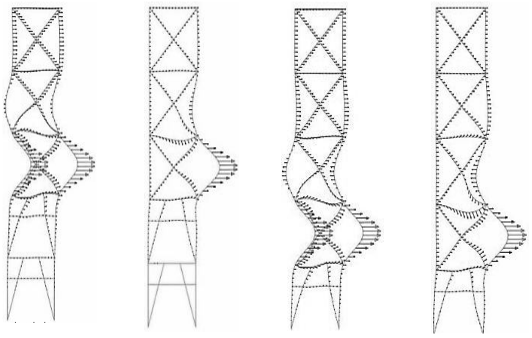
Figure 9: Case number 2 (A, B) of Table.4.i) and ii) of A) have Ch(c)+LN; iii) and iv) of A) have Ch(e)+LN; i) and ii) of B) has Ch(e)+LN. Modal displacements are shown by arrows.

Under the buckling consideration, it can be recommended here to use modified Chevron braces (preferably eccentric) only up-to two stories, and X braces at the upper stories. On inclusion of modified Chevron brace in bottom three stories of the considered frame configurations, buckling was observed at the bottom storey. Cases considered have been given in Figure 4, Figure 5, and Figure 6 and the values of critical load have been given in Table-4. Among them also, only the cases that showed buckling other than in the first storey were presented. All the cases presented here had the improved buckling behaviour under both the vertical and lateral loadings.

For case number 1 (A,B) of Table.4, it can be seen from the Figure 8 that on introduction of modified Chevron brace at lower stories (first two) and the X brace at the upper stories, the buckling of members can be observed at the stories above the modified Chevron brace.

For case number 2 (A,B) (weak beam-strong column) of Table-4, it can be seen from the Figure 9 that on introduction of modified Chevron brace at bottom stories (first two) and the X brace at the upper stories, the buckling of members can be observed at the stories above the modified Chevron brace (having eccentric Chevron brace). For modified Chevron brace having concentric Chevron brace in it, included in to bottom two stories, under lateral load, buckling was observed at the first storey, so it has not been presented here.





B: i) ii) iii) iv)

Figure 10: Case number 3 (A, B) of Table-4. i) and ii) have Ch(c)+LN; iii) and iv) have Ch(e)+LN. Modal displacement are shown by arrows.

In case number 3 (A,B) (weak beam-strong column) of Table-4, beam radius was kept as 4 cm but the lintel radius was made equal to the column radius as which was equal to 5 cm. It can be seen from the Figure 10 that on introduction of modified Chevron brace at lower stories (first two) and the X brace at the upper stories, the buckling of members can be observed at the stories above the modified Chevron brace as observed in the case 1 (A,B) of Table-4.

Conclusion

This paper discussed about a FEM based linear perturbation buckling analysis of the steel frames up-to 5 stories having only the braces, the lintel bands or the combination of Chevron braces with the lintel bands. The comparison has been done with a competent bracing type which has been found to perform well for most of its purposes, i.e. the X brace. Lintel bands have been found to work well against seismic forces whereas in this analytical study it has been shown that they also increase the buckling strength of the steel frames to a very considerable amount, especially against horizontal forces. All the selected types of the conventional braces were found to improve buckling resistance only for a limited size range in relation with the beam size. On including lintel bands, any such problem was not found, at-least for all the selected ranges of cross-sectional size of lintel bands (*equal to size of the beam and close to half of the beam size*). They resulted only into the advantageous configurations of the steel frames. Since, Chevron braces have been widely used because of their aesthetic appearance and the availability of opening area; lintel bands have been clubbed with Chevron braces as they won't hamper the movement/ opening area. Moreover, they will also provide support to the doors and the infill walls. In most of the cases, for the same radius of lintel band and the braces, the improvement in buckling load capacity was considerably significant. On using two types of bracing at different levels for improving the collapse characteristics, for the considered five storied frame configurations, using the modified eccentric Chevron brace (*i.e. with the lintel bands*) up-to bottom two stories and X brace at upper stories, buckling was observed at the level/stories above the stories having modified Chevron braced. Clubbing of the lintel bands in Chevron braced frames can result into a very good measure of retrofitting and incorporating the ductility considerations [21] along with the presented study can help in developing the design criteria for this new kind of braces having both the lintel bands and Chevron braces called as the multi- level eccentric braces.

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(Annexure-1)

Table-2: H/H0 and V/V0 Ratio Including Lintel Bands or the Cross Braces in the Steel Frames

Radius	B1S1		B1S1		B1S2		B1S2		B1S5		B1S5	
Bm, X/ LB (in cm)	H/H0 LB	H/H0 X	V/V0 LB	V/V0 X	H/H0 LB	H/H0 X	V/V0 LB	V/V0 X	H/H0 LB	H/H0 X	V/V0 LB	V/V0 X
3,0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3,3	1.09	1.09	1.31	6.62	1.26	**0.77**	1.50	9.97	2.73	1.17	1.68	13.24
4,0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4,3	1.30	**0.53**	1.22	4.78	1.72	**0.52**	1.27	5.86	2.57	1.13	1.31	6.78
4,4	1.35	1.38	1.63	5.73	1.98	1.51	1.74	7.26	2.75	1.33	1.85	8.60
5,0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5,3	1.45	**0.35**	1.17	4.01	2.02	**0.44**	1.18	4.41	2.11	1.05	1.20	4.53
5,4	1.56	1.00	1.48	4.69	2.26	1.31	1.50	5.29	2.28	1.18	1.55	5.61
5,5	1.66	1.79	1.93	5.61	2.47	1.42	1.98	6.33	2.48	1.30	2.05	7.14

(Annexure-2)

Table-3: H/H0 and V/V0 Ratio Including Struts or the Lintel Bands in the Chevron Braced Steel Frames

Radius	B1S1		B1S2		B1S5		B1S1		B1S2		B1S5	
Bm, Ch, St/LB	**H/H0**	**H/H0**	**H/H0**	**H/H0**	**H/H0**	**H/H0**	**V/V0**	**V/V0**	**V/V0**	**V/V0**	**V/V0**	**V/V0**
(in cm)	**St**	**LB**	**St**	**LB**	**St**	**LB**	**St**	**LB**	**St**	**LB**	**St**	**LB**
5,5c,5	1.69	1.93	2.04	2.33	1.56	3.58	4.27	10.46	4.85	11.22	5.42	13.19
5,5e,5	1.80	1.95	2.16	2.33	1.77	4.22	4.31	10.43	4.90	11.11	5.55	13.40
5,5c,4	1.62	1.80	1.95	2.17	1.55	3.33	4.26	9.55	4.85	10.18	5.41	11.99
5,5e,4	1.63	1.84	1.97	2.21	1.80	3.89	4.24	9.71	4.86	10.35	5.48	12.45
5,4c,4	**0.70**	**0.80**	**0.84**	**0.96**	1.46	2.29	4.23	9.30	4.67	9.90	5.09	11.22
5,4e,4	**0.67**	**0.78**	**0.80**	**0.93**	2.75	2.08	4.08	9.03	4.61	9.72	3.01	11.08
4,4c,4	1.11	1.28	1.00	1.15	1.53	2.73	4.76	11.49	6.04	13.91	7.19	16.28
4,4e,4	1.21	1.41	1.10	1.27	1.68	2.53	4.34	8.58	5.82	10.49	7.02	13.96
4,4c,3	1.05	1.16	**0.95**	1.05	1.52	2.50	4.75	8.87	6.03	10.67	7.17	12.69
4,4e,3	1.19	1.30	**0.99**	1.18	1.63	2.37	3.67	7.35	5.59	9.02	6.77	11.63
4,3c,3	**0.36**	**0.41**	**0.32**	**0.37**	0.77	0.88	4.70	7.32	5.74	8.93	6.66	10.62
4,3e,3	**0.34**	**0.43**	**0.32**	**0.39**	0.68	0.81	3.57	5.45	4.94	7.16	5.95	9.03

Table-4: Combination of the Modified Braces with the X Braces at Different Storey Levels

Case No.	Storeys	Beam, Brace	Ch(c) + LN, X		Ch(e) + LN, X	
	(Ch+LN), 'X'	**(r)**	**H/H0**	**V/V0**	**H/H0**	**V/V0**
1.A	(S1), 'S2,S3,S4,S5'	5,5	1.90	8.28	1.92	8.37
1.B	(S1,S2), 'S3,S4,S5'	5,5	3.41	11.2	3.47	11.34
2.A	(S1), 'S2,S3,S4,S5'	4,4	1.90	10.3	1.91	10.15
2.B	(S1,S2), 'S3,S4,S5'	4,4	2.69	13.9	2.52	13.70
3.A	(S1), 'S2,S3,S4,S5'	4,5	2.05	11.2	2.21	12.65
3.B	(S1,S2), 'S3,S4,S5'	4,5	3.94	17.0	4.00	17.07