CHAPTER 5: LINEAR BUCKLING ANALYSIS OF CHEVRON BRACED STEEL FRAMES AFTER INCLUDING LINTELS OR THE LINTEL BANDS

In this chapter, the capability of steel lintel bands and lintels (*struts*) after their inclusion in the steel frames (*braced or moment-resisting*) has been scrutinised for the improvement in the buckling strength/resistance. By adding the lintels or the lintel bands to the chevron braces frames, chevron braces were updated for improved buckling resistance. For comparison, the X braced frames were also analysed. X braces were found to be a constrained option with various limitations involved in selecting the size of the braces in combination with the size of the beams. On the other hand, the lintel bands were found to be consistent and work well in all the considered cases including the cases where the X braces failed to fulfil the purpose.

The buckling behaviour of eccentrically and concentrically chevron braced frames was studied by including both the lintel bands and lintels. It has been found that the lintel bands could be used as a good substitute of the conventional braces and could be included in the chevron braced frames to improve their buckling behaviour under both the lateral and vertical loads.

5.1. METHODOLOGY

Linear perturbation buckling analysis was done 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 and the results were compared with the frames having rigidly connected conventional cross-bracings. Then the analyses were done by including the lintel (s*trut*) or the lintel bands in the chevron braced NCBFs.

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 the radius of the braces/struts/ lintel bands was varied from the radius equal to the radius of the beam to 30 mm. As shown in Figure 5.1, height of each storey was 3m and the lintel band were attached at 2m from bottom to accommodate door and to improve buckling load capacity. Link length of the eccentric brace was taken as 1m, which availed the open area and improved the buckling behaviour.

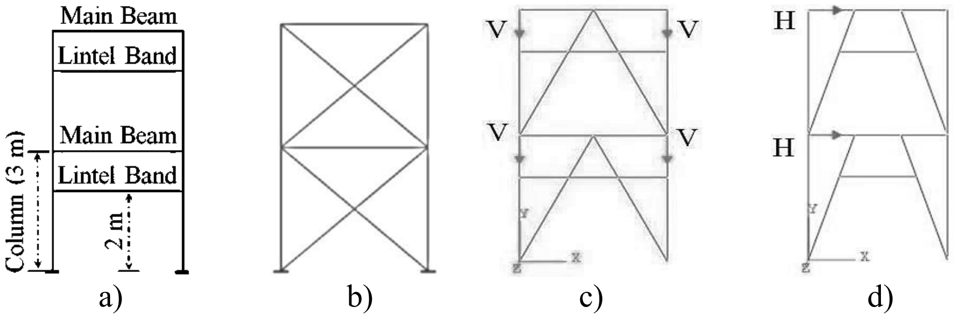


Figure 5.1 a) One bay two storied frame with lintel bands, b) X bracing, c) Vertical loading in chevron braced frame with lintel bands and d) Lateral loading in eccentric chevron braced frame with lintel

*Nomenclature:**H*** reresents lateral (*horizontal*) load (where, ***H0*** was for the bare frame case), ***V*** represents vertical load (where, ***V0*** was for the bare frame case), ***LB*** represents lintel band, ***X*** represents cross brace, ***Ch*** represents chevron brace, ***Bm*** represents beam, ***St*** represents lintel/ strut, P_{cr} represents critical Load and ***Br*** represents brace.

Main considered cases: Bare frames; frame having either lintel bands (***LB***) or the braces (***X*** or chevron brace); frames having chevron braces (*concentric/ eccentric*) with lintel bands (***Ch(c/e) + LB***) and frames having chevron braces (*concentric/ eccentric*) with lintel bands in lower stories and X braces in upper stories ((***Ch(c/e) + LB*****),** ***X***).

*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. *MN* means Mega-Newton.

5.2. RESULTS AND DISCUSSION

The results of buckling analysis were basically the critical loads values (P_{cr}), 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 load values for the bare frames have been given in Table.5.1 and the upcoming tables and graphs were formed as the ratios of these values.

Table 5.1 Critical load values (P_{cr}) 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

5.2.1 Lintel banded frames and X braced frames

In Table 5.2, for single bay and single-story frame, it can be seen that the lintel bands worked well for all the considered cross-sectional sizes of the beams with all the considered cross-sectional sizes of the other members. Bare frames have been considered as the references in the table. Looking at the improvement in buckling load capacity of the X-braced frames, they were found to work better than lintel banded frames against the vertical loads. But, the drawback of the X-braced frames was that event-though they increased buckling resistance against vertical loads, they failed to even reach the horizontal critical loads of the bare frames in many cases (*mainly the cases having a 3 cm member*). This shows the all-round utility of lintel bands as the lintel banded frames performed well under both vertical and lateral loadings

Table 5.2 *H/H0* and *V/V0* ratio for lintel banded or cross braced frames

Radius	*B1S1*				*B1S2*				*B1S5*			
Bm, (X/ LB)	***H/H0***	***H/H0***	***V/V0***	***V/V0***	***H/H0***	***H/H0***	***V/V0***	***V/V0***	***H/H0***	***H/H0***	***V/V0***	***V/V0***
(cm)	***LB***	***X***	***LB***	***X***	***LB***	***X***	***LB***	***X***	***LB***	***X***	***LB***	***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

In all the analyses with lintel bands, the improvement in buckling load was much significant in case of higher size (*cross-section*) 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 bare frame (*having 5 mm radius beam*). In case of both the lintel bands and the X-braces, keeping same cross-sectional size of beam and lintel bands/braces (*3,3; 4,4 cases*) showed better stability, even better than some cases of the higher size of beams.

A) i) ii) iii) iv) B) i) ii) iii) iv) C) i) ii) iii) iv)

Figure 5.2 Buckling modes of lintel banded steel frames. A) B1S1 frame, B) B1S2 frame, C) B1S5 frame. i) V0, ii) V with LB, iii) H0, iv) H with LB

The changes in buckling modes of frame on the introduction of the lintel bands in it has been shown in Figure 5.2. 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 introduction of lintel band improved the buckling behaviour (See Table. 5.2) in such a way that minor benefits were achieved under vertical loading but under lateral loading, it significantly restrained the buckling of the columns (See Figure 5.2). X-braces performed better under vertical loading. As the number of stories rose, the effect of X-bracing in controlling the buckling diminished rapidly under lateral loading whereas the effect of lintel band was of consistent nature for all the considered stories.

In Table 5.2, it can be seen that the improvement in *V/V0* ratio was observed in all the considered cases. *V/V0* ratio was higher with the X-braced frames but this ratio was greater than 1 in all the cases of lintel banded frames. Whereas, such is not the situation in case of *H/H0* ratio; as in two cases of *B1S1* frame configuration and in three cases of *B1S2* frame configuration, the *H/H0* ratio for X-braced frame was less than 1.

5.2.2 Chevron Braced Frames

From the bar chart (Figure 5.3), it can be seen that *H/V* ratio values in the bare frame condition (*4,0; 5,0 cases on radius-axis*) were very much higher than the ratio values in braced frame condition for any of the storey height. Even-though *H/V* ratio doesn't give any idea about the improvement in the critical load values, it does represent the change of the behaviour of the strength under vertical and horizontal loading after the modification of the configuration of the frame. The behaviour of braced frame under various loadings changed very much in comparison to bare frame condition.

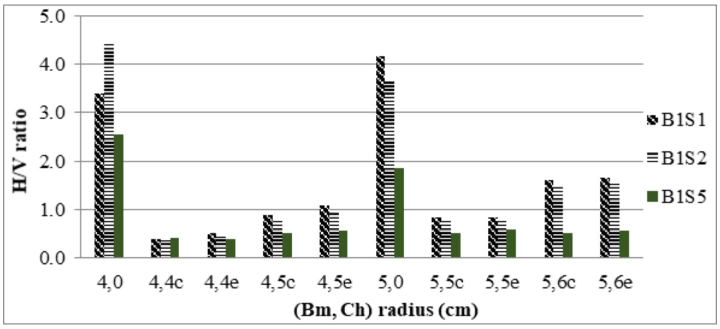
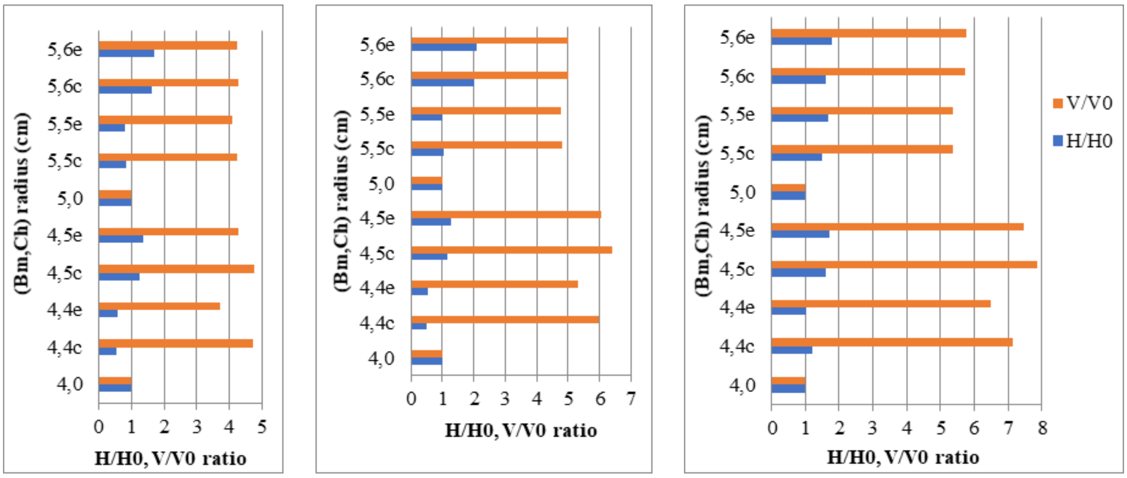


Figure 5.3 Bar chart of H/V ratio including chevron braces in the steel frames

Referring Figure 5.4, in all the cases of chevron braced frames, value of *V/V0* was higher than 1, which indicated the improvement in the buckling load capacity under vertical loading. On inclusion of chevron braces, out of total 24 cases (*both, concentrically and eccentrically braced*), in four cases of *B1S1* configurations and two cases of the *B1S2* configuration, *H/H0* values was less than 1.



a) B1S1 b) B1S2 c) B1S5

Figure 5.4 *H/H0* and *V/V0* ratio of the chevron braced frames

5.2.3 Chevron braced frames after including strut (*St*) or lintel bands (*LB*)

The column radius has been kept fixed as 5 cm throughout the analysis. Referring Table 5.3, Critical load value under vertical load was found to increase on the inclusion of the strut or lintel bands in the chevron braced frames, represented by V/V0 ratio.

Table 5.3 *H/H0* and *V/V0* ratio of chevron braced frame using lintel/ lintel bands

Radius	***B1S1***		***B1S2***		***B1S5***		***B1S1***		***B1S2***		***B1S5***	
Bm, Ch, St/LB	***H/H0***		***H/H0***		***H/H0***		***V/V0***		***V/V0***		***V/V0***	
(in cm)	***St***	***LB***	***St***	***LB***	***St***	***LB***	***St***	***LB***	***St***	***LB***	***St***	***LB***
5,5*c*,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
5,5*e*,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
5,5*c*,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
5,5*e*,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
5,4*c*,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
5,4*e*,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
4,4*c*,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
4,4*e*,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
4,4*c*,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
4,4*e*,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
4,3*c*,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
4,3*e*,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

For weak beam - strong column (*having beams of 4 cm radius*), including lintel bands of 4 cm, rise in *H/H0* ratio was observed. This showed the capability of this combination to satisfy the ductile detailing criteria and strength criteria Whereas, the *H/H0* ratio for the chevron braced frames alone was significantly less than 1 in these cases for the *B1S1* and *B1S2* configurations (see Figure 5.4). In some cases, where the brace size was less than the beam, even on adding struts/ lintel bands, the *H/H0* ratio was less than 1.

For *B1S1* and *B1S2* chevron braced frames having lintels (*struts*) or lintel bands of radius equal to that of chevron brace but less than that of the beam, were found to be less stable. All *B1S2* configurations having struts of radius 3 cm, were found to have *H/H0* ratio less than 1. In the cases where the radius (*section size*) of the beam and braces was kept same as the column, the *H/H0* was significantly higher than 1.5 in most of the cases on inclusion of the lintels or the lintel bands, whereas for the lone brace frame b1S1 configuration, *H/H0* was less than 1). Addition of lintel bands was found to be more beneficial than the addition of strut/ lintels with the chevron braces.

5.2.4 Combination of modified bracing and conventional bracing at different stories

By combining two types 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 previous results that X braces work better than the unmodified chevron braces under both vertical and lateral loading in most of the cases. So, the modified chevron braces and the X-braces were selected for the combination. *B1S5* frame configuration has been considered for combination of braces. Keeping same cross-section of both the beams and braces, their radius was varied from 5 cm to 4 cm.

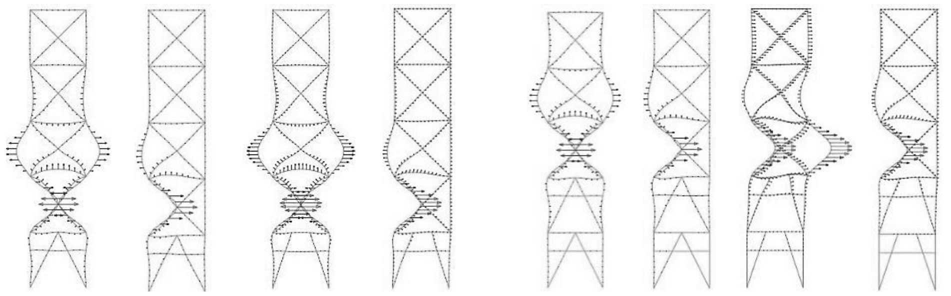
In all the frames braced throughout with same type of conventional braces, buckling was observed in the ground storey itself. Placing X braces at the bottom stories and the modified chevron braced cases (*eccentric or concentric, including lintel bands*) at upper stories was also not found to be beneficial as the buckling occurred at the bottom most storey under both vertical and lateral loadings.

Table 5.4 Combination of the modified braces with the X braces at different storey levels

Case No.	***(Ch+LB) - (X)***	**Beam, Brace**	***Ch(c) + LN, X***		***Ch(e) + LN, X***	
	Stories	**(in cm)**	***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	11.21	3.47	11.34
2 A	*(S1) - (S2,S3,S4,S5)*	4,4	1.90	10.31	1.91	10.15
2 B	*(S1,S2) - (S3,S4,S5)*	4,4	2.69	13.92	2.52	13.70

The combination of modified chevron braces at bottom stories and the X-braces at upper stories was found to be workable; as in many cases, the buckling was observed in upper stories rather than starting with the bottom storey. Under the buckling consideration, it has been recommended here to use modified chevron braces (*preferably with eccentric chevron*; *up-to two stories were found beneficial here*) 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.

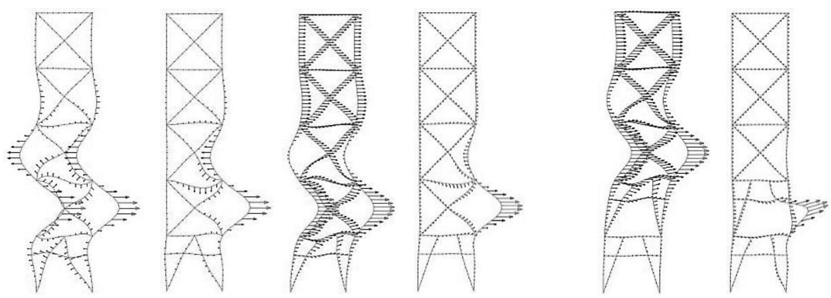
The values of critical loads for the cases considered have been given have been given in Table 5.4 and based on the cases numbered in the Table 5.4, buckling modes have been presented in Figure 5.5 and Figure 5.6. In stories column of Table 5.4, numbered stories where '*Ch + LB'* were included have been written in the first bracket and numbered stories where X-braces were included have been written in the under second bracket. All the cases shown here in figures were found to improve the buckling behaviour of the framed structure under both vertical and lateral loadings.



A) i) *V* ii) *H* iii) *V* iv) *H* B) i) *V* ii) *H* ii) *V* iv) *H*

Figure 5.5 Case 1(A, B) of Table 5.4. i) and ii) have *Ch(c)+LB*; iii) and iv) have *Ch(e)+LB* Note: Modal displacements have been shown by arrows.

Referring Figure 5.5 for case number 1 (A, B) of Table 5.4, it has been observed that on introduction of modified chevron brace at lower stories (*up-to first two*) and the *X*-brace at the upper stories, the buckling of members was observed at the stories above the modified chevron braced stories.



A) i) *V* ii) *H* iii) *V* iv) *H* B) i) *V* ii) *H*

Figure 5.6 Case number 2 (A, B) of Table 5.4. i) and ii) of A) have *Ch(c)+LB*; iii) and iv) of A) have *Ch(e)+LB*; i) and ii) of B) have *Ch(e)+LB* only
Note: Modal displacements have been shown by arrows.

Referring Figure 5.6 for case number 2 (A, B) (*weak beam-strong column*) of Table 5.4 it has been observed that on having the modified chevron brace at bottom stories (*up-to first two*) and the *X* -brace at the upper stories, the buckling of members was observed at the stories above the modified chevron braced stories (*having eccentric chevron brace*). For the modified chevron braced frames having lintel bands added with the concentric chevron braces in the bottom two stories, under lateral load, buckling was observed at the first storey, so they have not been included in the buckling improvement cases.

5.3 CONCLUDING REMARKS

The addition of lintel bands (*even with small sections*) in the moment frames was found to improve the lateral load resistance to a very good extent. The addition of the lintel bands or the lintels (*struts*) into the existing chevron NCBFs was found to significantly improve their lateral load resistance for most of the cases. *X*-braces were found to work better than the unmodified chevron braced frames. For most of the considered cases, the addition of lintel bands was found to work better the addition of lintels (*struts*) and considered cases having *X*-braces (*under lateral loading*). On addition of lintel band in the chevron braced frame, the improvement in the lateral load capacity was checked here in this part and the improvement in the ductility (*inelastic deformations, hysteretic behaviour*) has been checked in an upcoming chapter.

With the implementation of modified (*with lintel-bands*) chevron braces (*up-to two stories*) and X-braces (*upper stories*) in different bracing levels of the 5-storied frame, the buckling was mostly observed above the bracing levels having modified chevron braces. Conclusions have been discussed elaborately in the last chapter, 'SUMMARY AND CONCLUSIONS'.

SECTION 2: NON-LINEAR ANALYSIS OF OLDER BRACED FRAMES

After the buckling of a brace in compression, chevron NCBFs experience serious strength degradation, excessive beam deflection and consequently the condition of unbalanced forces acting on the beams. Such problems have not been faced by the diagonal or the cross-braced frames and mostly, they have been limited to use in the moderate seismic zones. The problem of unbalanced forces acting on the beams in chevron braced frames has been found to become worse when beam deflects excessively at its connection (*with the braces*); as it would result into ineffectiveness of the remaining braces resisting loads through tensile action. Such behaviour of the steel braced frame can't be ascertained though the linear buckling analysis (*linear analysis can only ascertain the strength until the elastic limit*). Linear analysis was found to be a good option for the analysis of the bridge and to calculate the critical load capacity of braced frames. Linear buckling analysis wasn't found suitable for applying cyclic loading and wouldn't represent the non-linear behaviour of the structure. For renovative modifications not requiring internal modifications, beam elements were used and where the contact-based analyses were required, shell elements were used in the numerical analysis.

The non-linear numerical analysis was conducted using FEM based simulation software (*Abaqus CAE*) to access the inelastic behaviour of braced frames under cyclic loading. The renovation strategies were devised to improve the inelastic behaviour of the chevron braced frames (*both concentric and eccentric*). The outcomes of the analysis for studying the behaviour of the braced frame after retrofitting were the hysteretic behaviour, plastic energy dissipation, the beam deflection, rotation of links (*eccentrically braced frames*), maximum stress levels and deformation of core part of the developed buckling restrained braces. Chapter-wise explanation of renovation strategies has been given below.