CHAPTER 10: SUMMARY AND CONCLUSIONS

This research was conducted to improve the buckling behaviour of older steel braced frames and in doing so, the set objectives were properly satisfied. The steel braced frames were analysed for both strength and ductility. The strength consideration was basically focused on improving the buckling load capacity of the braced frames. Such analyses would help the braced frame to take both the vertical and the lateral loads like extraneous live loads, impact loads, wind loads and water front based loads (tides or Tsunami etc.). But as a general conception, the braces have always been considered to be a part of lateral load resisting system and have also been referred as seismic force resisting systems (SFRS). Where, the bracing arrangement can be sacrificed to save the main structural components (beams/ columns). major contribution of bracing system has to be the dissipation of the energy imparted to the structure by the repeated lateral loading (seismic activity/ earthquakes). So, in the next phase of this work the seismic load resistance of the braced frames was improved and was verified by conducting non-linear analyses.

The mechanism of each bracing configuration can be significantly different from other. In case of the occurrence of a moderate seismic activity, the primary role of the concentric braces is to undergo inelastic deformation and maintain the main structural components to remain in the elastic state. Whereas, the role of the eccentrically braced frames is to sacrifice only the link part and maintain all other components to remain in the elastic state, including the braces. The conclusions drawn from individual analyses conducted under both linear and non-linear phases of analyses have been presented here.

10.1 SECTION 1: LINEAR ANALYSIS OF STEEL STRUCTURES

10.1.1 Experimental and numerical buckling analysis of steel frames

It has been observed that the buckling modes and the critical loads obtained from the FEM based simulations were as expected theoretically and were found to be in agreement with the experimental results. With the variation in the cross-section of the buckling member in relation with the cross-section of the connecting members, the buckling modes got affected significantly and consequently these variations in the buckling modes influenced the effective length and critical load. Where the section of the buckling member was nearly equal to the connected member, the symmetric buckling mode for the parallel buckling members in the plane of buckling deformation was less expected.

For a buckling bar connected to a higher section bar (*creating a fixed end condition*), symmetric buckling of parallel members could be observed. For the condition of I/I_0 ratio equal to 1, smaller effective length ratios were obtained for the smaller size of bars (*close to 0.5*), as seen in Table 2.3. When the section of the buckling bars was kept constant, the rigidity of connection increased with the increase in the section of the connecting bars. For two different cases, having the section of buckling bars and connecting bars as different, but I/I_0 ratios as same for both the cases, the case having smaller size buckling bar had less effective length ratio, i.e., higher rigidity.

10.1.2 Renovation technique for promotion of the loading class of an old steel truss bridge

It has been conveyed through many reports that many members of conventionally designed old metal truss bridges have more capacity than their designated load capacity but the vehicle loads and the pattern of moving load on the bridges have also changed with time. To promote the loading class of the selected bridge, in the analysis of the bridge, the old through-type steel truss bridge was converted into a new type of bridge, concrete-filled prestressed (CFP) truss bridge, just by utilizing the spaces available in the sections of the main members. This configuration would overcome the deficiencies of the old through-type single span truss bridges in comparison to the current design practices of composite or double composite bridges without affecting the historic appearance and aesthetics of these bridges. The old through-type simply supported bridges made-up of open built-up sections can be easily promoted to higher loading class by following the expeditious and handy procedure discussed here.

10.1.3 Linear buckling analysis of braced frames under axial and lateral loadings: the effect of bracing location

A FEM based linear perturbation buckling analysis was conducted in this section. All the considered braces have been found to improve stability against vertical loading. In most of the cases, a symmetric brace with a symmetric arrangement of bracing was expected to work well against both vertical and lateral load and avoids premature buckling to some extent. Fully X braced frames have been found to increase stability under both vertical and horizontal load. For diagonal braced frame, under lateral load, in most of the cases, the brace buckled prematurely. Under the lateral loading, when the diagonal brace was in tension, then also, in many cases the overall stability of structure has been found to be less than that of bare frame due to premature buckling of beam or column.

It has been observed that the lateral buckling resistance was mostly influenced by very few braces at few lower stories; but here, the 'diagonal' brace having the same cross-section as that of beams and columns has been found to buckled prematurely at very low P_{cr} value, when placed in lower stories in a multi-storied frame. It has also been found that when the diagonal brace having slenderness ratio (not cross-section) equal to beam and column was used, even then the stability against lateral loading was lower than that of the bare frame for both cases: the singly braced frame having a maximum value of critical load having just one brace (*at any particular bracing level*) and for the fully braced frame, for the considered B1S3 frame configuration.

Against lateral load buckling, the inclusion of tension brace along with the compression brace has been found to provide more stability to the structure. Under vertical load, in general, the bottom braces contributed more in resisting the buckling. Also reducing the brace size at higher stories was not found to influence the overall stability of structure much. But, for the substantial buckling resistance increase and no significant change in stiffness of stories, bracing every story has been considered significant. As the number of the stories increase, the effect of P_{cr} values reduces drastically for X-braced frames, but in the case of chevron braced, the reduction is minor (*i.e., less fluctuating with rise in the height of the frame*).

For multiple bay frames, many researchers have suggested to necessarily brace the central bays portion for improving both strength and stability against lateral and vertical loading. When checked from buckling (*strength*) perspective, after bracing more than one bay, central bay bracing was not found to be the best in all the cases. In this study, it has been found that for more than one bay bracing, bracing at least both-side corner bays gave higher buckling load capacity and were found to be the crucial elements for increasing the buckling load resistance of frame. In the arrangements not having corners braces, the beams of the un-braced end corner bay buckled at a very low buckling load. Inclusion of more braces was not found to be better (*also from economy perspective*) to resist the buckling for various bracing types and configurations. To prevent stiffness related issues, bracing stories throughout would be a compulsion but to brace throughout bay-wise wasn't found to be a compulsion. For bay-wise bracing, in some cases it has been found that even appropriately bracing half of the total bays provided nearly equal or sometimes more buckling resistance in comparison to full bracing.

10.1.4 Linear buckling analysis of chevron braced steel frames after including lintels or the lintel bands

A FEM based linear perturbation buckling analysis was conducted here. The unbraced steel frames having only the lintel bands, only the chevron braces or the chevron braces with added lintels (*struts*) or the lintel bands, have been analysed here. The comparison was done with a competent bracing type, which performed well for most of its purposes, i.e., the X braces. Lintel bands in the unbraced RCC framed structures have always been found to work well against seismic forces and here also in the steel frames, they were found to work well against monotonic lateral loading from the stability perspective. In this analytical study it has also been found that in most of the cases the lintel bands on adding into the chevron braced frames also increase the buckling load capacity of the steel frames to a very considerable amount, especially against horizontal forces.

All the available conventional braces were found to improve buckling resistance only for a limited cross-sectional size range in relation with the beam size. On including the lintels or the lintel bands along with the chevron braces, such problems were less prominent here and mostly resulted into an advantageous configuration. Clubbing of lintel bands in chevron braced frames resulted into a very good measure of renovation and also prove to be a good configuration for the design of new braced frames (*would also provide support to the doors and infill walls*). In most of the cases, for the same cross-sectional size of lintel band and the braces, the improvement in buckling load capacity was significant. In other cases, two types of bracing were introduced at different levels/ stories for improving the collapse characteristics. For the considered five storied frame configurations, using the modified eccentric chevron brace (*i.e., with lintel bands*) up-to bottom two stories and the X brace at the remaining upper stories, buckling was observed in the members at the level/stories above the stories having modified chevron braced.

10.2 SECTION 2: NON-LINEAR ANALYSIS OF OLDER BRACED FRAMES

10.2.1 Use of vertical and diagonal members to upgrade the steel braced frames

Eccentrically Braced Frames

In the conventional eccentrically braced frames, plastic dissipation by the members other than the link portion was found to be significant (*ideally, link has to dissipate most of the energy*); consequently, the strength degradation at later stages of the cyclic loading was also significant. The older/ conventional eccentrically braced frames that have been in the working condition can be strengthened with ease without causing much disruption to the occupants and with minimal structural intervention. Steel off-take was very low and wouldn't require complex arrangements and skilled labour.

After the introduction of reforming measures, till 6% drift range (3% drift limit), all the reformed cases showed maximum plastic dissipation through shear/rotation of the link (*desirable*) and the hysteresis loop was both balanced and stable. In some cases, where effective length of the braces was higher; the plastic dissipation at the later stages of loading was also contributed by the braces and the beam outside the link. This resulted in the degradation of strength at later stages of loading in these cases. In a case, where the additional diagonal was connected to the middle of the existing brace; even-though at the later stages of the loading the braces began to involve in the plastic dissipation but the plastic dissipation by shear/rotation of the link was significantly higher throughout the loading process and the strength degradation was minimal.

Concentrically Braced Frames (CBFs): Reducing Beam Deflection

In the current SCBF provisions (*in the seismic codes*), beams capable of overcoming the unbalanced forces have been adopted (*strong enough to avoid excessive deflection of the beams*). Whereas, the old designed chevron braced frames (NCBFs) faced various problems after the buckling of a compression brace (*causing unbalanced forces on the beam which in turn results in the excessive deflection of the beam*). Two types of arrangements to upgrade the chevron bracing were generated here as dual-Y brace (DYB); one out of them was the combination of X-brace and Y-brace and other was the combination of zipper brace and Y-brace. Both the bracing configurations were found to improve the behaviour of overall frame under cyclic/repetitive loading.

All the configurations analysed here were able to significantly reduce the beam deflection. It was found that the additional members (*vertical or diagonal*) connected at the centre of the brace worked better than other cases. As in these cases, the inelastic activity in the 'beam' was considerably reduced (*helped braces to work effectively*) and the desired inelastic activity (*plastic/energy dissipation*) in the braces was increased. The plastic dissipation was close to 1.5 higher than that in the initial state and the lateral load resistance (*recognised here as critical load*) was improved close to 2.5 times the initial state. These outcomes (*deflection, critical load and plastic dissipation*) clearly indicate that the improvement in the overall structural behaviour (*both ductility-wise and strength-wise*) of the concentric chevron braced frames.

Concentrically Braced Frames (CBFs): Hysteretic Behaviour

It was found that the members connected at the centre of the brace both diagonal and vertical were found to be better than the member connected at the other locations of the brace. Here, the peaks in the hysteresis curve were reduced significantly but not rectified completely as it resulted into the degradation of strength in the later stages of loading. Even though this renovation measure rectified many deficiencies of the old braced frames in comparison to the current design provisions based braced frames but the hysteretic behaviour of the CBFs still required major improvements (*in the later work, i.e., by converting CBF into a BRBF, this deficiency was also rectified*).

10.2.2 Transforming chevron brace configuration into a multi-level eccentric-chevron (MLEC)

The chevron braced frames representing old and existing chevron braced frames were upgraded by transforming them into MLEC braced frame. The steel take-off increment was just 9%. Upper part of the MLEC braces didn't undergo buckling in any case. The chevrons CBF after upgrade (MLEC) were found to have improved strength, less beam deflection and better hysteretic behaviour. For chevron EBFs updated as MLEC braced frames, the energy dissipation increased and the undesirable behaviour observed in the old designed eccentric brace was rectified.

Rather than the yielding of the beam, the considerable link rotations of both the beam-included link and the lintel-band-included link were found to be the primary source of energy dissipation. It was also found that the total output energy curves were periodic and the mean of curves was zero for the MLEC braced frames generated out of the eccentrically braced frames as they were better both strength-wise (*higher critical buckling load*) and ductility-wise (*stable and balanced hysteresis curves*). The generally observed peaks in the hysteresis curves of the CBFs were rectified here but little strength degradation in the hysteresis curves of the CBFs was still observed here.

10.2.3 Conversion of non-ductile chevron brace into stiffened-casing dual-sleeve buckling restrained brace

The EBFs were upgraded to a very good extent by using previous two strategies (*additional verticals/ diagonals or the MLEC braces*). The behavior of the CBFs was also significantly improved (*beam deflection was reduced, energy dissipation was improved, hysteretic behaviour was also improved significantly in comparison to the initial state of the CBF*) but unlike the eccentrically braced frames that dissipated most of their energy through shear deformation of the link portion, CBFs were still dissipating energy through the tensile stresses and the buckling of the braces. Due to buckling, the strength degradation was inevitable there. So, the CBFs were to be improved by a measure which could avoid the detrimental effect of buckling.

To improve the hysteretic behaviour of the CBFs to a very stable and balanced level, the chevron braces were by converted into a new type of buckling restrained brace, which were called here as stiffened-casing dual-sleeve BRB (*SCDS-BRB*). Here, the old NCBF specimen was adapted from the experimental report on chevron braced frames by Wakabayashi *et. al.* (1967). As desired, the hysteresis curves of the SCDS-BRB frames were symmetric on both the compression and the tension side.

The nodal displacements of the core were quite symmetric longitudinally in comparison to many other previously reported BRBs. The stiffened casing avoided both the local bulging and the global buckling of the overall BRB (*these problems have been mostly observed in the all-steel BRBs*). It was found that higher stiffness of casing helped in dissipating more energy. Most importantly, the rotational deformation concentrated in the region just outside the buckling restraining mechanism (*as mentioned in AISC 2016*) was limited by inserting the casing in the secondary sleeve. The specimen with wide terminalends of the core (*transition ends*) was found to be weaker than others and didn't satisfy the limits of design parameters. The out-plane buckling case would be the best choice for upgrade amongst all of the presented cases as it would dissipate more energy, satisfy the codal provisions and the general convention of the out-plane deformation of core.

AISC (2016) recommends the quasi-static loading for the testing of BRBs but the real potential of these SCDS-BRBs would be tested on implementing the real-time near-fault earthquake dynamic loading in a full-size specimen of 3 m (*or above*) height with relatively sized braces (*there, the width of the core would be about 80% (or more) of the total web depth*). Increasing dynamic yield strength with strain hardening and symmetrical nodal displacements of the core, clearly reflects its potential to effectively work for loading cycles resulting into the drift higher than the applied ones.

10.3 SCOPE FOR FURTHER WORKS

1. Full-scale experimentation to explore about the parameters other than the ones studied here (*buckling load and hysteretic behaviour*); like connection failure etc. after the implementation of the strategies presented here.

2. Extensive dynamic loading experimentation; utilizing real time near fault earthquake time –history data: Even AISC (2016) seismic code restrained from providing the recommendation for dynamic loading to test BRBs in wake of the unavailability of sufficient experimentation.

3. As it has been established here in this work that the BRB configuration can also be achieved from the existing bracing configuration; it provides a lot of scope to work on developing new and better BRB configurations from the existing/ older bracing configurations.