CHAPTER 9: ORIGIONAL CONTRIBUTIONS

9.1 INTRODUCTION

In this chapter, the summary of the contributions made in the field of science and technology thorough this research work has been listed. The specific contributions made to either theory, design procedure, or the introduction of an assessment process by each of the work conducted here have been discussed. To discuss the novelty of the work, the focus has been given to the scientific and fundamental originality of this research work.

9.2 LINEAR ANALYSIS OF STEEL STRUCTURES

Initially, a prototype of a welded underslung bridge was constructed and loaded in such a way that the particular members were expected to undergo buckling. The purpose of this work was to experimentally and numerically analyse the buckling behaviour (*buckling mode shapes, critical loads and the effective length*) of the compression members in the welded steel frames.

Through this study, various contributions were made to the theory of the buckling analysis. A method for the assessment/ calculation of effective length using simulated results was suggested here, utilizing the concept of moment equation. This study provided an insight into the buckling behaviour (*buckling modes and effective length ratio*) of the frame members with the change in their cross-section and the cross-section of the members connected with those buckling members. These observations can be incorporated for the improving the design procedure of the welded steel frames. This work also acknowledged some of the future scopes enlisted by Webber *et. al.* (2015).

Next, a retrofitting technique was devised for an existing (*around 60 years old*) through-type simply-supported steel truss bridge (*having open-web sectioned main members*) located in Uttarkashi district of the Uttarakhand state of India. Main contribution here was the introduction of a stress-based approach to promote the loading class of the bridge (*suitable to carry the highest loading, Class-A loading, as per the current IRC6 code; 70R(W)vehicles and 40T bogie loads in case of emergency*) without hampering its historical appearance (*indicated as a major concern in various survey reports*).

The upgraded state of the old bridge model was achieved by appropriately utilizing the limited space available within the sections of the main members. To strengthening measures were introduced to best suit the particular stress zones. The concepts of the composite bridges (*combined action of slab and top chord*), double-composite bridges and the concrete filled steel tube bridges (*concrete filling in the top chords and the intermediate support potions of the bottom chords*) have been mostly used to construct 'new' under-slug bridges. As most of these under-slung bridges have been the well-designed ones, prestressing has not been found necessary in them but prestressing has been generally used to retrofit the through-type bridges. In the through-type bridge analyzed here, slab was in tension zone and the prestressing alone was not found sufficient as it was severely detrimental to the other components of the bridge. So, rather than just prestressing the bottom chord, both concreting (*in the compression members by converting open-web sections into closed tube sections by closing them*) and appropriate prestressing (*along the bottom chord*) were implemented here to work together. The combination was such that the vertical deflection of the bridge was considerable low (*slab would experience minimal tensile stresses*) and buckling of the cross-braces (*connecting the truss frames of the bridge*) was avoided without changing them (*as the compressive stresses were properly handled by concrete filled main compression members*).

Next, linear buckling analysis was conducted to assess the effect of bracing location and the effect of addition of lintels/ lintel bands. The behavior was examined in terms of critical load (P_{cr}) values obtained from numerical analysis using the linear perturbation buckling analysis method or the Eigen value method. The steel frames were individually subjected to vertical or horizontal (*lateral loading*) loadings.

Here, an assessment process was introduced for better design and analysis of steel braced frames related to the effects of bracing on the buckling strength. By following the assessment process, a better buckling behaviour could be achieved by incorporating appropriate number of braces with appropriate configuration and arrangement of braces at appropriate locations in the steel frame. Next, the buckling behaviour of the steel frame after incorporating lintel bands (*as struts between columns*) or the lintels (*as struts between the eccentric/ concentric chevron braces*) was analyzed and compared with other type of bracing. The horizontal lintel bands in RCC structures and the braces in the steel frames have been generally used in earthquake resistant structures to improve their seismic performance and to resist sway. In this numerical study, steel lintel bands 'in combination with chevron braces' were examined for their capability to resist buckling in braced steel frames. As per the analyses (*including the non-linear analysis of the MLEC braces, done in later*), the lintel bands can be included in the new design and construction practices related to the chevron braced steel frames and can also be used to retrofit the existing chevron braced frames.

9.3 NON-LINEAR ANALYSIS OF OLDER STEEL BRACED FRAMES

The main contributions in this section include the development of expeditious and handy (*easy to execute, least disruptive and least interventive*) retrofitting strategies rather than just following the conventional trend of formulating the costly and sophisticated methods (*structurally interventive and occupationally disruptive*) to upgrade the old braced frames. The problems encountered in the previous retrofitting methods have been listed precisely in the newly added section of Chapter 1, Section 1.4.4, 'Identification of Research Gaps'. In the course of devising strategies, various new types of bracing configurations/ types were developed (MLEC and SCDS-BRB).

According to Wakabayashi *et. al.* (1978), very compact braces (*very compact means plastic braces, slenderness ratio around 30*) caused the failure of the columns (*which is outrightly undesirable*) due to induction of excessive axial stresses in them. It was also found that reducing the slenderness ratio of the braces to half of its initial value by using a much compact brace provided just 9% improvement in the non-linear inelastic-buckling capacity instead of the theoretically expected 400% (Roeder 1989). Not just from non-linear inelastic analysis done by Wakabayashi (1978) and Roeder (1989) but also from the linear buckling analysis done in Chapter 4 of this thesis, it can be clearly understood that increasing the slenderness ratio of the brace by increasing its section was meagerly helpful but severely detrimental in some cases. But unlike the detrimental effects observed on reducing the effective length by increasing the moment of inertia of the brace section, it was understood from the linear buckling analysis done in the Chapter 5 that reducing the effective length by introduction of a node could significantly improve the buckling behavior of the steel brace frame. To verify this observation, development of many design and construction methodologies was attempted by conducting non-linear analysis. Finally, three discrete kinds of configurations of braces were developed.

The working of one of the developed configurations involved the combined action of the Y-brace and X-brace and the working of other involved the combination of Y-brace and Zipper braced frame. Whereas, the third has a complete dimension of working, it was called here as multi-level eccentric chevron (MLEC) braced frame. Even-though in the existing state, it was just a NCBF, but after inclusion of lintel band its working involved combined action of two eccentric braces at each story level. Using these configurations, most of the parameters defining the structural behaviour were improved, including the reduction in the beam deflection, which would avoid the complete replacement of such beams with the new SCBF compliant beams. These concepts can be incorporated to design new braced configurations and can be used to retrofit the existing braced frames.

Mostly in the severe earthquake zones, some of the braces in the braced frames are replaced by new BRBs. No previous research work has been encountered where an existing non-ductile brace was transformed into a ductile buckling-restrained brace (BRB). In the last work, transformation of an existing non-ductile braced frame into a new type of ductile-BRBF (*stiffened-casing dual-sleeve BRB*) was attempted. Unlike the newly prefabricated All-Steel BRBs, this transformed BRB had an externally stiffened casing to decouple the axial stress and buckling and a new concept of sleeves around the casing to control the rotation at the of the upper end of the core (*rotational demands can be a serious issue in some cases, as per AISC 2016*) was also introduced. The detrimental effects observed in most of the 'newly developed' All-Steel BRBs (*like global/local buckling of BRB, local bulging of casing etc.*) were not predominant here. Which clearly indicated towards its potential to be implemented as a newly designed All-Steel BRB as well as to serve the purpose of retrofitting, as presented in this work.

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.