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Numerical Analysis of Chevron Braced Frames retrofitted using Vertical and Diagonal Brace Members

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Abstract

This article discusses about the retrofitting of the existing chevron braced frames, constructed before the induction of the concept of thespecial concentrically braced frames (SCBF) braced frames. Two arrangements of upgraded bracing were developed; one configuration was inspired by X-brace and Y brace while the other was inspired by Zipper brace and Y-brace. Both arrangements resulted into unique dual half Y-brace (DHYB). The numerical analysis was done by using Abaqus software. The outcomes of the analysis for studying the behaviour of the braced frame after retrofitting were the hysteretic behaviour, plastic energy dissipation and the beam deflection. In most of the cases, retrofitting using the above mentioned technique provided a more stable and balanced hysteretic behaviour, improved energy dissipation, reduced beam deflection. This method of retrofitting would cause minimal structural intervention and least disruption to the occupants.

Keywords: Chevron brace, Retrofitting, Cyclic loading, Numerical Analysis

1. Introduction

Many of the tall building in current times and few decades back were made using steel as a major construction material. As far as steel structures are concerned, most of them are generally equipped with addition members for the lateral load resistance and for the seismic energy dissipation that are called as primary seismic force resisting systems. These primary seismic force resisting systems include various types systems but the most common type is the braced frames. Few decades back, when seismic codes were in pre-mature state of development (*before the development of special concentrically braced frames, SCBF)*, many braced frames were already in existence. Major concern of these frames has been presented in the concentrically braced frames as they are said to be uncertain under the severe repetitive lateral loads (Popov 1983). After the buckling of one of the braces under compression, sudden decrease in the compressive strength of the brace can be observed (Sabelli 2001, Sen *et.al*. 2016). But when the brace is considered in the whole frame, the strength degradation of the whole structure is not severely affected in most of the cases (Popov*et.al*. 1987). When considering old concentric chevron braced frames an unbalanced force resulting from braces acts on the beam, because of which strong beam has been suggested in the SCBF provisions (ASCE 2016). But in the old chevron braced frames this problem still exists (Sen *et.al*. 2014). Many researchers have studied the behaviour of braced frame constructed in olden days. Wakabayashi *et.al*. (1977, 1980) studied the behaviour of concentric braced frames. Popov *et. al.* (1983, 1987) studied the behaviour of eccentrically braced frames. Further studies related to connections were done by Roeder (1989). Some found the old braced frames to be capable of resisting seismic loads and found braces or the weak beams as secondary members for retrofitting (Sen *et.al*. 2014 and Sizemore *et.al*. 2017) and some found it necessary to replace weak beams with SCBF based beams (Rai and Goel 2003). Tsuji (1988) experimentally showed the drawbacks of using weak beam in chevron braced steel frames.

Numerical analysis has been considered as one of tools for understanding the behaviour of steel braced frames. It is difficult to access the manufacturing defects and imperfections, locally concentrated errors in the actual structures as they vary for every experiment and for every loading setup conducted in various locations throughout the world. Even-though the local behaviour of the braced frame was not captured in the numerical model by Sen *et.al*. (2014) and Sizemore *et.al*. (2017) but the global behaviour matched with the experimental one. Narayan *et. al*. (2020) found that the Abaqus software (2014) simulated the welded frame behaviour very much in competence with the experimented one. The effective length of the buckling members was closely achieved and the size of the connected member also affected the effective length. Rai and Goel (2003) suggested three measures to curb the effects of the deficiencies in chevron braced frames. Concrete filling in the hollow tube steel section (HSS) braces, replacing chevron braces with two story X-braces, replacing the

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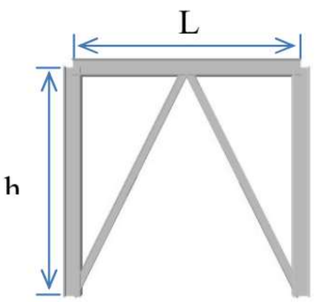
beams with SCBF based beams. They described those upgrading measures as disruptive to the occupants, and required extensive structural inventions. Narayan and Pathak (2021; 2021) devised some very handy strategies for the upgrade of the braced frames, which were neither disruptive to the occupants nor required extensive structural inventions.

Wakabayashi *et.al*. (1977) found that bringing the slenderness of the braces less than 30 had detrimental effects on the behaviour of the braced frames under repeated lateral loads and Narayan and Pathak (2020) found that the bringing the slenderness close that of beams and columns had a detrimental effects on the columns. Present study provides a simple and effective means to overcome some of the major deficiencies of the chevron braced frames without causing extensive structural intervention or disruption to the occupants. This has been done without replacing any member and without increasing the size of the brace.

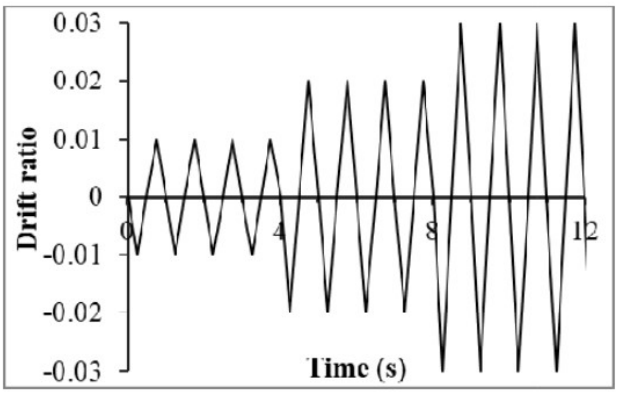
2. Methodology and specifications of specimens

In the investigation by Sloat (2014), before the induction of the concept of SCBFs, most of the steel buildings were equipped with the wide flange chevron braces made-up of ASTM-A36 steel, which was equivalent to the JIS-SS40 steel. To replicate the steel structure in numerical analysis, material properties and member specifications were taken from an old experimental study (Wakabayashi *et.al*. 1980). Where the height of the frame (h) and the width of the bay (L)were 1.4 m and all the members were wide-flange sections made-up of JIS-SS40 steel. All the members were rigidly connected (as shown in Fig.1.a).

The experimental results given in the report by Wakabayashi (1980) were validated using numerical simulation in Abaqus software (2014) and numerical simulation results were found to be in correlation with the experimental ones. Based on same frames as used in the experimental report, chevron braces (as shown in Fig.1.a) were analysed for the cyclic loading (shown in Fig.1.b). The existing state was then modified by incorporating diagonal and vertical bracing members (as shown in Fig.2).



(a)



(b)

Fig.1. a) Considered chevron braced frame b) Displacement load history.

3. Results and discussion

The results of the numerical simulation of selected chevron braced frames were obtained in the form hysteresis loops and the plastic dissipation time-history graphs. In the unmodified state of the chevron braced frame (Ch), the hysteresis loop shown in Fig.3.a, was neither stable (strength degradation and the sudden initial peaks/spikes) nor balanced (differences in compression and tension sides). The energy dissipation has been shown in Fig.3.b.

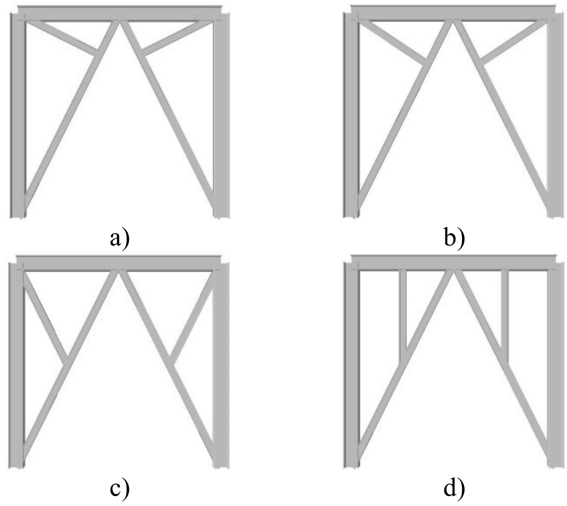
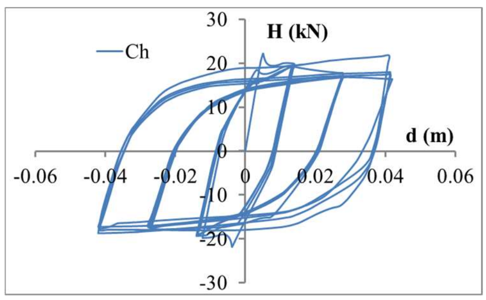
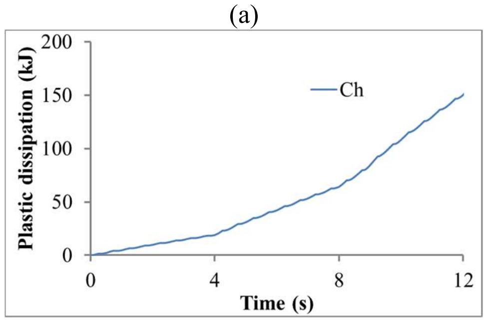


Fig.2. Additional bracing members a) perpendicular to the existing brace, b) connected to existing brace at one-fourth height of the frame, c) connected to brace at central height, d) vertical at brace from central height of frame connected to the beam.

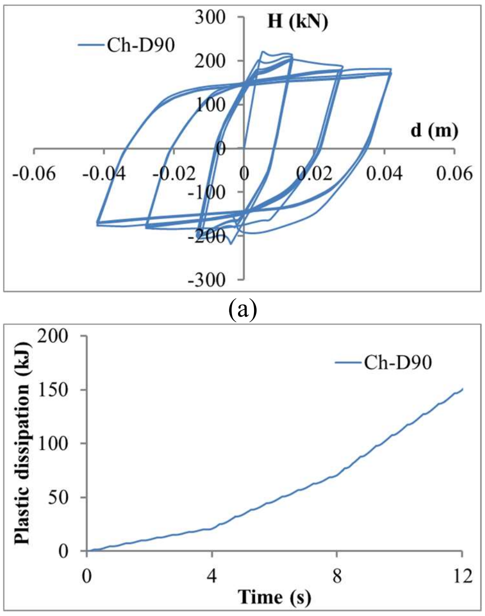


(a)



(b)

Fig.3. a) Hysteresis loop for chevron braced frame (Ch), b) Energy dissipation graph.



(a)

(b)

Fig.4. a) Hysteresis loop for modified braced frame (Ch-D90), b) Energy dissipation graph.

To reform the behaviour of chevron braced frames, four modified configurations were analysed. Three configurations included additional diagonal brace members and one configuration included additional vertical brace. Their analysis results are discussed below.

Member from beam column joint perpendicular to the brace (Ch-D90)

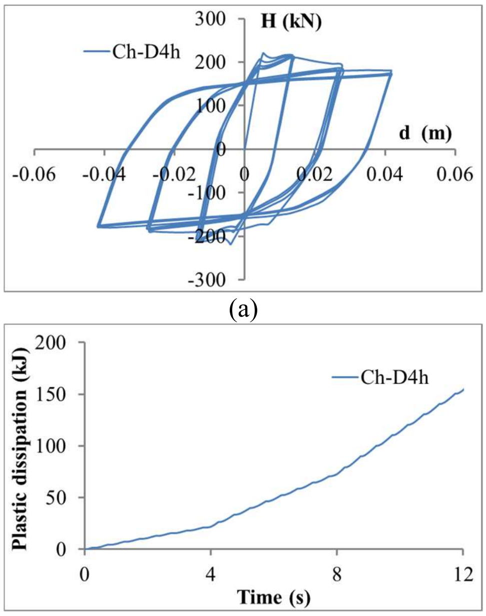
The inelastic activity in the beam was reduced in comparison to the unmodified case. The hysteresis loop became more balanced (see Fig.4.a) but the improvements were not significant as the energy dissipation (see Fig.4.b) was not improved and the beam was still contributing significantly in the inelastic activity along with the braces.

Additional brace from beam column joint to brace at one fourth height from top (Ch-D4h)

The inelastic activity in the beam was reduced in comparison to the unmodified case. The hysteresis loop became more balanced (see Fig.5.a) but the improvements were not significant as the energy dissipation (see Fig.5.b) was not improved and the beam was still contributing in the inelastic activity along with the braces.

Diagonal member from the centre of the brace (Ch-D)

For the modified configuration having an additional diagonal member connected from the beam column connection to the brace at the central height of the frame, the results were very much acceptable and reformed in comparison to the unmodified configuration. The sudden decreasing peaks/spikes observed in the hysteresis loops of the unmodified chevron braced configuration in the initial loading stages were diminished, the hysteresis loops were more balanced and stable (see Fig.6.a). The energy dissipation was also improved considerably (see Fig.6.b). The inelastic activity in braces was predominant as expected from a well-designed braced frame.



(a)

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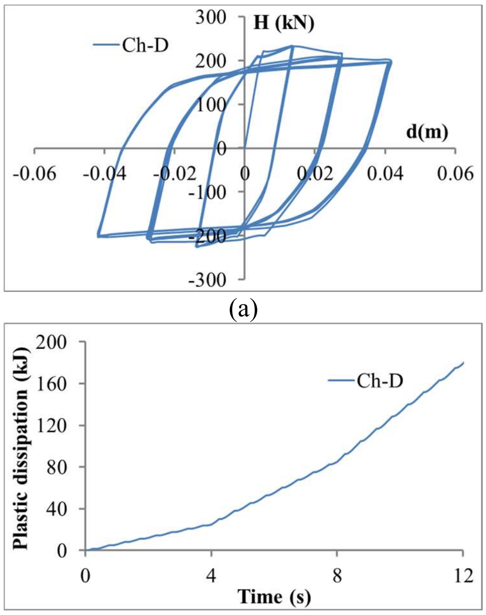
Fig.5. a) Hysteresis loop for modified braced frame (Ch-D4h), b) Energy dissipation graph.



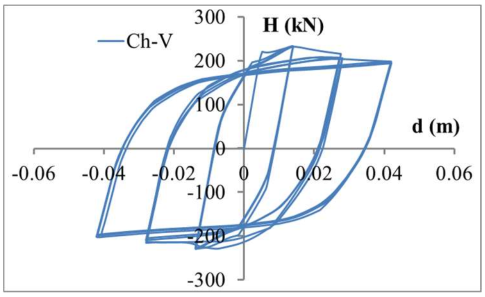
(a)

(b)

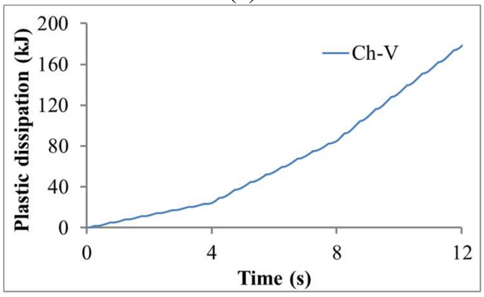
Fig.6. a) Hysteresis loop for modified braced frame (Ch-D), b) Energy dissipation graph.

Vertical member from the centre of the brace (Ch-V)

In the modified configuration where an additional vertical from central height of the frame connected from the existing brace to the beam, all the purposes were satisfactorily achieved. The sudden decreasing peaks/spikes observed in the hysteresis loops of the unmodified chevron braced configuration in the initial loading stages were diminished, the hysteresis loops were more balanced and stable (see Fig.7.a). The energy dissipation was also improved considerably (see Fig.7.b). This configuration improved the



(a)



(b)

Fig.7. a) Hysteresis loop for modified braced frame (Ch-V), b) Energy dissipation graph.

behaviour of the braced frame significantly as the inelastic activity in the beam was minimised and the braces were found tobe the most predominant members in dissipating the energy as expected.

The retrofitting methods introduced here were found to improve the behaviour of the braced steel frames considerably under the effect of repetitive/cyclic lateral loading. In unmodified braced frame it can be seen that in third set of loading the beam deflection is so abrupt in changes from 10 mm to 35 mm on load reversal. In all the retrofitted cases, there is no abrupt change in beam deflection and looked like following a regular pattern. In the braced frames where additional members were connected to the centre of the brace, the beam deflection at the mean position is zero, whereas in all other cases beam continues to achieve a deflected shape. The major take from this analysis was that the members connected at the centre of the brace were found improve the behaviour of the old chevron braced frame under cyclic loading in comparison to the other cases.

4. Conclusion

It has been observed that the old designed steel braced frames lacked some features that are considered important in the currently available seismic codes. An attempt to improve the behaviour of such old braced frames under cyclic loading was made in the present article.

1. Two types of arrangements of upgraded chevron bracing were obtained;
   a) One was similar to the combination of X-brace and Y-brace
   b) Other was the combination of zipper brace and Y-brace.
2. Both the bracing configurations were found to improve the behaviour of overall frame under cyclic/repetitive loading. Peaks/spikes in the hysteresis loops in the initial stage of the loading were controlled, strength degradation was reduced and the plastic dissipation was significantly high.
3. It was found that the improvisation provided by the addition members connected at the central height of the braces (both diagonal and vertical) was better than the member connected at the other locations of the brace.
4. The retrofitting methods suggested here don't require any replacement to avoid disruption to occupants and to avoid extensive structural intervention.
5. This retrofitting measure rectified many deficiencies of the old braced frames in comparison to the current design provisions based braced frames.

Disclosures

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