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# IMPROVING THE STRUCTURAL BEHAVIOUR OF THE CONCENTRIC CHEVRON BRACED FRAMES UNDER CYCLIC LOADING

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## ABSTRACT.

In this paper, a method of controlling the excessive deflection of the beams in the chevron braced frames (based on the braced frames constructed pre-1988) under the repetitive loads has been discussed. The problem of unbalanced forces acting on the beams in these braced frames has been found to become worse when beam deflects excessively at the connections of the braces. Four different bracing configurations of chevron braced frame obtained after including additional diagonal and vertical bracing members were numerically analysed using FEM based software. Along with the reduction in the undesirable beam deflection; the significant improvement in the lateral load resistance and the plastic dissipation was also observed. The reduction in beam deflection can reduce the uncertainty about the behaviour of chevron braces by avoiding the local buckling of beam. Steel take-off was close to just 9% of that in the existing state. It can be executed without excessive hardship and would cause least structural intervention with minimal disruption to the occupants of the building.

***Key-words**: Chevron brace; Beam deflection; Numerical analysis; Cyclic loading*

## 1. INTRODUCTION

Finite element method (FEM) based analyses (*conducted in many of the past research literatures*) were found to simulate the real world behaviour of the structures to a very good degree and were able compute the values of the output parameters to a very good approximation. Sen *et. al.* (2014) and Sizemore *et. al.* (2017) showed that the global behaviour of framed structures can be accessed by doing the computer based (FEM) numerical analysis. Based on various literatures confirming the capability of FEM based software to simulate the behaviour; FEM based models of the braced frames representative of old braced frames (*constructed before the development of SCBF provisions*) having weak beams were simulated using ABAQUS software (2014) in the paper presented here. The investigation done by Sloat (2014) clearly indicated that the chevron braced frames were preferred in olden days because of their architectural appearance and the availability of easy passage/ openings. At that time, chevron braced frames were not well-designed in competence with the current seismic codes (Sen *et. al.* 2016 and Rai and Goel 2003).

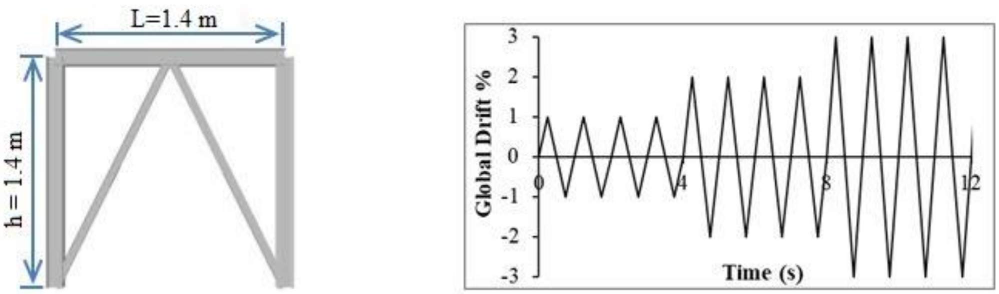
Many of the preliminary researches on concentric braced frames (CBFs) were done by Wakabayashi et. al. (1977 and 1980) and researches on eccentric braced frames (EBFs) were majorly done by Popov et. al. (1983 and 1987). Further researches on braced frames (especially on the connections in the braced frames) were done by Roeder et. al. (1987) and Roeder (1989). One of the major problems in CBFs was the excessive deflection of the beams under lateral loads in the chevron braced frames. This behaviour of beams also had an adverse effect on the other frame members (the columns), connections and the primary lateral load resisting systems (Robert and Trembley, 2000, Sabelli, 2001).Rai and Goyal (2003) suggested to replace the existing beams with the special concentric braced frame (SCBF) design based beams to overcome the excessive deflection of the beams. According to them, the methods suggested by them required severe structural intervention and would cause serious disruptions to the occupants of the building. Like many other researchers they used different fraction of strength (0.55) for the residual compressive strength after buckling. No universal certainty/conclusion has been reached regarding the residual compressive strength in CBFs, as it has been varied from 0 to 0.55 by various researchers and codal provisions.

After buckling of a brace in an initial loading cycle, such braces have been found to possess significant amount of residual strength left for the upcoming loading cycles, which has been often neglected while designing (Kanyilmaz, 2017). Decreasing the slenderness ratio of the braces below 30 resulted in a sudden decrement of strength of the overall frame at the later stage of the cyclic loading (Wakabayashi et al. 1977). In support of the same, Narayan and Pathak (2020) found that when the slenderness of the braces was close to the slenderness of the beams and columns, it resulted into strength loss and adverse effects on the columns.

In this paper, to reduce the beam deflection avoiding the problems occurred due to the increment in the brace size, four different bracing configurations of chevron braced frame obtained after including additional diagonal and vertical bracing members were numerically analysed. Three configurations had additional diagonal members connected to the existing brace at the various locations and one configuration had additional vertical members.

## 2. METHODOLOGY AND SPECIFICATIONS OF SPECIMENS

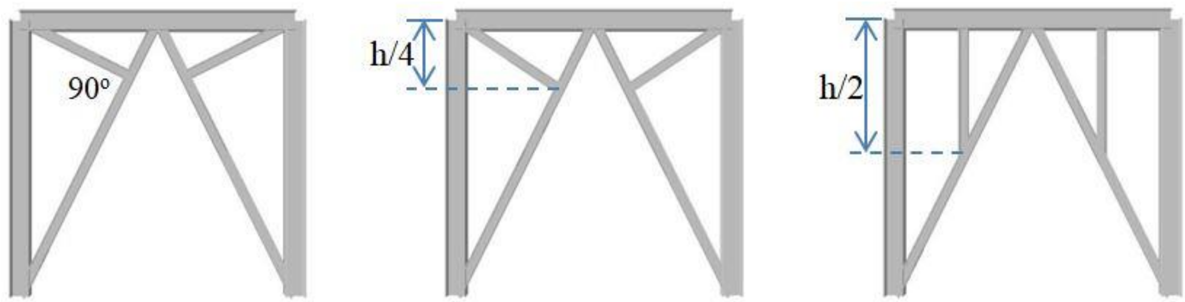
The methodologies applied in the present numerical analysis were such that their employment in the existing concentric chevron braced frame would improve both strength and ductility, without extensive structural intervention and the disruption to occupants. Problems of extensive structural intervention and disruption to occupants were encountered in the upgrading methodologies suggested by Rai and Goel (2003). Such problems were not encountered in the upgrading strategies suggested by Narayan and Pathak (2022, 2021). The initial configuration of chevron brace and the loading configuration have been shown in Fig.1.a and b, respectively.




a) b)

**Figure 1.** a) Chevron braced frame, b) Cyclic Loading protocol

The main objectives of the renovation or retrofitting techniques are to provide the desired structural behaviour to the structure, to avoid the complete replacement and to do it cost-effectively. These considerations were very effectively justified by the work presented here. The method of retrofitting used here involved the addition of vertical and diagonal members connected to the braces. The strategies presented here are so handy that they can be very easily executed using the brace connection design considerations prevalent in the country or region. Four configurations were analysed numerically using ABAQUS Software (2014). Three configurations had additional diagonal bracing connected from beam column end connection; perpendicular to the existing braces (Fig.2.a), at one-fourth height of frame from top (Fig.2.b), at central height of frame (similar to that in Fig.2.b). In one configuration, vertical members were connected to the beam from the existing braces (at central height of the frame as shown in Fig. 2.c).




a) Perpendicular diagonal b) diagonal from one-fourth height c) vertical member

**Figure 2**. Additional members connected to the braces and frame.

The design methodologies for the connections have changed drastically over the decades. The gusset plates were of arbitrary size in olden braced frame constructions. Many of the braced frames were directly welded. The structural steel manufactured nowadays wouldn't represent the steel used in olden constructions as it varies in strength and properties in comparison to the one manufactured in olden days. So, to replicate a generalized old braced frame, the material properties and the member sections were referred from an old experimental report (Wakabayashi et. al. 1980). Here, design provisions from various countries were referred (JSCE, 2009, IS:800, 2007 and ANSI/AISC 341-16, 2016) along with the contemporary reports about the olden construction practices (Wakabayashi et. al. 1977, 1980). Various frame configurations were considered in these reports but the cross-section of frame members and the braces was same in all the cases. All the members (wide-flange sections) were made-up of JIS-SS400 steel as given in the report by Wakabayashi. Connections were the directly welded rigid connections. Specification of the member sections adapted from Wakabayashi et. al. (1980) has been provided in the Table 1.

Table.1 Specifications of the member sections

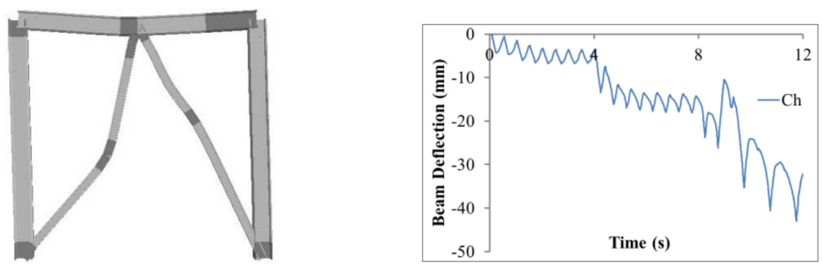
| Members | Section (values in mm) | Yield Strength (MPa) | Ultimate strength (MPa) |
|---|---|---|---|
| **Beam and Column** | 100×100×6×8 | 276 | 424 |
| **Braces** | 50×50×6×6 | 270 | 409 |
| **Additional members** | 50×50×6×6 | 270 | 409 |

Narayan et. al. (2020) found ABAQUS Software (2014) to be capable of simulating welded connection in proximity with the actual welded connections. The FEM based numerical analysis of braced frames was conducted for the repetitive load. As used by Narayan et. al. (2020), the structure was modelled using the beam elements. Combined hardening was incorporated along with the material and geometrical non-linearity. Displacement controlled quasi-static analysis was performed. Before doing the numerical simulation for the considered cases, the process was validated for the experimental results given in the report by Wakabayashi et. al. (1980). The results showed very good correlation with the experimental results, similar to that by Mamaghani (2017). It was able to capture the deformation of the beam at various points of times in the loading time history and the control of excessive beam deflection was ascertained.

## 3. RESULTS AND DISCUSSION

The results presented here are in the form of deformed profile of the selected specimen at the time of maximum deformation, their critical buckling loads (in Mega Newton) when the horizontal load has been applied at the beam column end connection and the maximum vertical deflection of the beam (in mm). At the end of the information about the deformation, the comparison of plastic dissipation has been presented to understand the improvement in the energy dissipation capacity after the upgrade.

The deformation profile of the unmodified chevron braced frame showing the yielding zones at a particular time of loading has been shown in Fig.3.a and the time history plot of the beam deflection has been shown in Fig.3.b. The inelastic activity in beam is predominant (along with that in the braces) and the deflection of beam at 3% roof drift is close to 45 mm.




a) b)

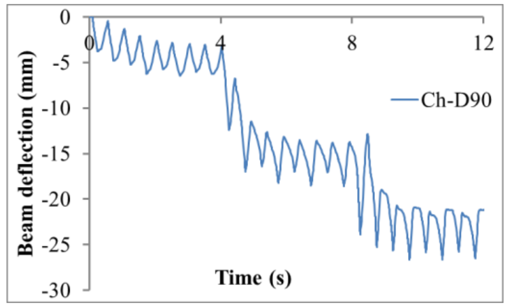
b)

**Figure 3.** a) Deformed chevron braced (ch) frame (with yielding zones), b) beam deflection

It can be seen that the inelastic action of beam is also predominant along with the inelastic action of the braces, which is not recommended. As the lateral drift was increased, the deflection of beam also increased with time. To avoid problems caused by beam deflection, various modifications were done for the retrofitting/upgrade of the chevron braced frames.

### 3.1 Additional diagonal brace perpendicular to existing brace (Ch-D90)

Diagonal braces were connected from the beam-column connection end, perpendicular to the existing brace. The deformed shape at a particular time has been shown in the Fig.4.a. Inelastic activity was profound only in the lower part of braces (as the effective length was considerably high). The deflection of beam was very much reduced from maximum of close to 45 mm to less than 30 mm (as shown in Fig.4.b) but the inelastic activity in the beam at various points of times was significant, so one purpose of reducing beam deflection was satisfied but the drawback of beam deflection was not completely rectified in this case.

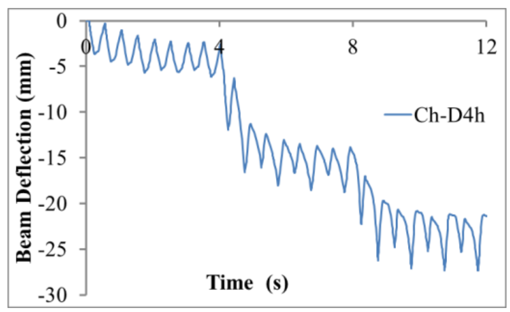



a) b)

**Figure 4.** a) Chevron brace frame with additional brace, b) beam deflection

### 3.2 Additional diagonal brace at one fourth height from top (Ch-D4h)

In the existing chevron braced frame, an additional diagonal brace from the beam-column connection end to the existing brace was connected rigidly at a vertical height of one-fourth of the total story height. The deformed shape at a particular time has been shown in the Fig.5.a. Inelastic activity was profound only in the lower part of braces (as the effective length was considerably high). The deflection of beam was considerably reduced from close to 45 mm to less than 30 mm (as shown in Fig.5.b) but out of all the considered modified braced frames, this configuration had maximum inelastic activity in the beam.



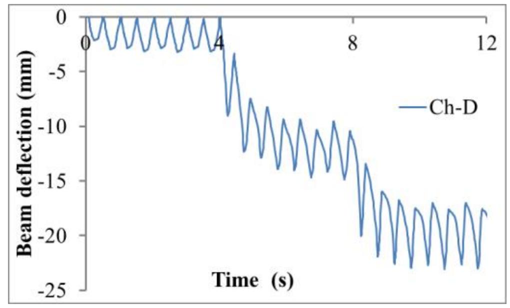

a) b)

**Figure 5.** a) Chevron brace frame with additional brace, b) beam deflection

### 3.3 Additional diagonal brace at central height (Ch-D)

In the existing chevron braced frame, an additional diagonal brace from the beam-column connection end to the existing brace was connected rigidly at a half of the story height. The deformed shape at a particular time has been shown in the Fig.6.a. Inelastic activity in the beams was not that profound. Inelastic activity was profound only in the upper part of braces and as the effective length was reduced considerably it can be expected to have both strength and ductility. This configuration is one of the most acceptable configurations amongst all the considered configurations as it satisfies both the purposes of reducing the beam deflection (from close to 45 mm to less than 25 mm) and reducing the inelastic activity in the beam section, which in turn improves the inelastic activity in the braces.

a)

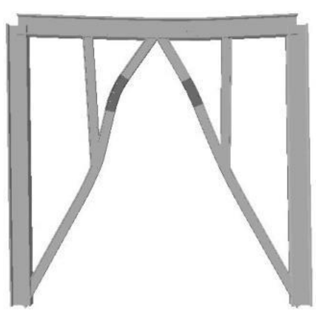



b)

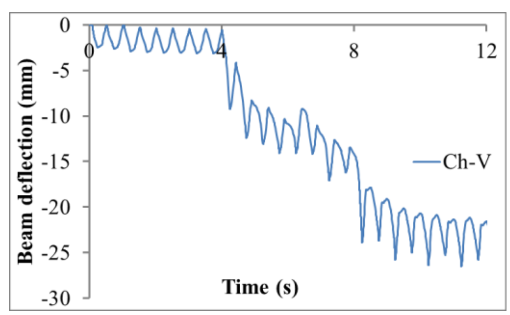
**Figure 6.** a) Chevron brace frame with additional brace, b) beam deflection

### 3.4 Additional vertical brace from the centre of the brace (Ch-V)

In the existing chevron braced frame, an additional diagonal brace was connected from the brace at the central height of the frame perpendicular to the beam. The deformed shape at a particular time has been shown in the Fig.7.a. This configuration experienced least inelastic activity in the beam as two additional members acted as supports. Inelastic activity was profound only in the upper part of braces and as the effective length was reduced considerably it is expected to have both strength and ductility. This configuration is also one of the most acceptable configurations amongst all the considered configurations as it satisfies both the purposes of reducing the beam deflection (from close to 45 mm to less than 30 mm) and reducing the inelastic activity in the beam section, which in turn improves the inelastic activity in the braces.



a)




b)

**Figure 7.** a) Chevron brace frame with additional brace, b) beam deflection

The retrofitting methods introduced here were found to reduce the beam deflections considerably under the effect of repetitive/cyclic lateral loading. In unmodified braced frame, it has been seen that in third set of loading, the beam deflection was highly abrupt as it changes from 10 mm to 35 mm on load reversal. In all the retrofitted cases, there are no such high abrupt changes in the beam deflection. In the braced frames where additional members were connected to the centre of the brace, the beam deflection were quite regular and at the mean position beam deflection was close to zero, especially with the additional diagonal bracing members connected to the existing braces at the mid-height.

### 3.5 Strength and Plastic dissipation

It can be concluded from many research articles that the reduction in beam deflection can result into an improved behaviour of the concentrically braced frames under cyclic/seismic loading. To do so, they had suggested providing a stronger beam. Also, as per the seismic provisions (AISC (2016), JSCE (2009), IS (2007)), to design a new SCBF (special concentrically braced frames), stronger beams have been recommended. But in the existing old/conventionally constructed braced frames, replacement of beams with stronger beams (SCBF based design) in multi-storied buildings can cause serious disruption (complete vacation) to the occupants, would require intensive structural intervention, heavy equipment/machines and very skilled workers. Over that, replacing the braces with stronger braces was not found to be a favourable solution as it was found to cause structural problems in other members and make the structural behaviour of frame more uncertain and less ductile (Wakabayashi et. al. 1977, Narayan and Pathak 2020). All these design and construction related constraints were satisfactorily overcome by very handy and economical strategies suggested here. Not only the behaviour under repeated loading was improved but the strength/resistance to the lateral load was also improved significantly. The critical loads (Pcr) under lateral/horizontal (H) and vertical loads (V) have been provided in the Table 2.

**Table 2.** Critical load values of the considered braced frames

| Specimen Configuration: | | Ch | Ch-D90 | Ch-D4h | Ch-D | Ch-V |
|---|---|---|---|---|---|---|
| $P_{cr}$ | **H (in MN)** | 1.02 | 1.43 | 1.60 | 2.48 | 2.46 |
| | **V (in MN)** | 10.6 | 10.8 | 10.8 | 10.9 | 10.7 |

In the method suggested here, neither beam nor the braces were replaced. The effective length of braces was reduced by providing a node (connection between brace and additional diagonal). As an outcome, the beam deflection was significantly reduced (close to half of the initial deflection). The improvement in the structural behaviour can be well understood from the improvement in the plastic dissipation of the conventional frame, as shown in Fig.8.

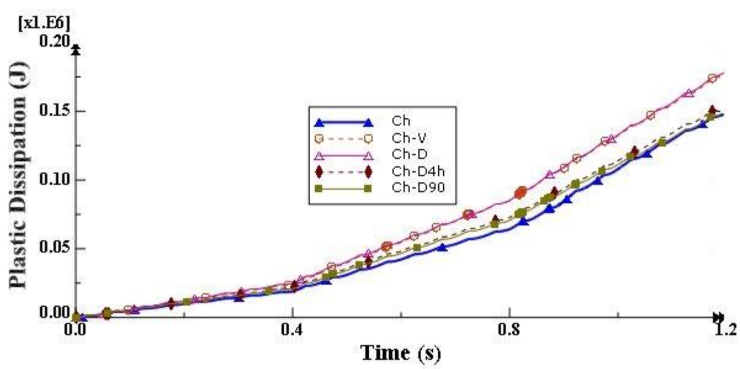



**Figure 8.** Time history plot for the plastic dissipation in various configurations

Even-though all the selected configurations reduced the beam deflection significantly but for the bracing configurations where the addition members were connected at the centre of the existing brace, the plastic dissipation was close to 1.5 time that of the initial unmodified configuration. Compared to the critical load for the initial state, Ch, critical loads were also close to 2.5 times higher in the cases where the additional members were connected to the centre of the existing braces.

## 4. CONCLUSION

In the currently used SCBF provisions in the seismic codes, beams are made capable of overcoming the unbalanced forces and are made strong enough to avoid excessive deflection of the beams. Whereas, the old designed chevron braced frames faces 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). An attempt to control the deflection of the beams in such old braced frames under cyclic loading was made in the present article. All the configurations analysed here were able to solve the purpose of reducing the beam deflection. It was found that the members connected at the centre of the brace both diagonal and vertical worked better, as the inelastic activity in the beam was considerably reduced (helped braces to work effectively) in comparison to the desired inelastic activity (plastic/energy dissipation)in the braces. 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 overall structural behaviour (both ductility-wise and strength-wise) of the concentric Chevron braced frame was significantly improved. The retrofitting methods suggested here didn’t require any replacement to avoid disruption to occupants and to avoid extensive structural intervention.

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