Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Detailed Numerical Validation of Gapped Inclined Bracing System (GIB) as a retrofitting strategy for soft-story buildings

Rabin Thapa [a], Kshitij C. Shrestha [b]

[a, b] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] 078MSStE014.rabin@pcampus.edu.np, [b] Kshitij.shrestha@pcampus.edu.np

Abstract

This study validates Gapped Inclined Bracing (GIB) as a retrofitting strategy in seismic-prone regions like Nepal. GIB involves an inclined brace with a gap element, activated when column lateral drift exceeds a threshold. Utilizing DIANA software, this study validates experiment conducted by Salmon J et al, employing solid element modeling for both conventional and retrofitted frames. A simplified model for GIB as compression-only element is proposed. The simplified model accurately captures peak responses for both systems. Results confirm GIB retrofitting significantly improves structural performance, addressing soft-story vulnerabilities. The modeling approach employed proves suitable for future seismic retrofitting research, contributing to earthquake-resistant building techniques.

Keywords

Soft-story, Retrofit, GIB, Gap element, DIANA

1. Introduction

Seismically active regions, like Nepal, present unique challenges for structural safety. Earthquakes' dynamic nature necessitates meticulous engineering to mitigate risks. Structural issues in such areas often stem from various factors, including architectural choices and construction practices. A key problem is the soft-story issue . NBC-105 (2020) [1] defines a soft story as one whose lateral stiffness of the lateral-force resisting system is less than 70 percent of the lateral-force-resisting system stiffness in an adjacent story above or below, or less than 80 percent of the average lateral-force-resisting system stiffness of the three stories above or below. In a country such as Nepal, seismic vulnerability often arises inadvertently due to the removal or reduction of rigid non-structural partitions on a specific floor of a building. Furthermore, the structural analysis and design of buildings typically focus solely on the bare frame, disregarding the stiffness contribution of infill walls. As a result, the ground floor is intentionally left open for commercial and parking use, while masonry infill is introduced in the upper stories, leading to variations in stiffness resulting in the soft-story. In-addition to meet the architectural requirement and social requirement of the structure, soft story also provides the structural benefit of isolation effect to the stories above [2, 3].

Different approaches have been made to retrofit soft story buildings. Seismic retrofitting guidelines of Nepal has been developed for the retrofitting of buildings. Addition of V-bracing, X-bracing to counter soft story problems, addition of shear walls, steel jacketing of columns [4], increasing the size of column of ground floor suggested by different codes [5, 6], addition of viscous dampers, using of double yield buckling resistance bracing [7]etc. are some conventional retrofitting strategy for soft story problem.Several building codes, including the Indian Standard 2002 [5], Israel Standard 1995 [6], recommend increasing the dimensions of ground floor beams and columns by a factor of 2.1 to 3 in order to address the soft story issue. However, research conducted by Kaushik et al [8] revealed that reinforcing the frame did not alter the collapse mechanism compared to an open ground-story frame that remained unmodified. Despite the reinforcement, plastic hinges remained concentrated in the columns of the ground floor due to their increased stiffness. As a result, the frame still experienced failure primarily due to the flexural failure of these columns rather than the ground floor beams. Despite of various retrofitting strategies, they take account of soft story problem by increasing the stiffness, most of them either affects the functionality and aesthetic of the building or they are costly and kills the isolation benefit provided to upper story by soft story buildings. There is need of an innovative retrofitting strategy which takes in account of all the drawbacks of conventional retrofitting strategy and is provided by Gapped Inclined Bracings (GIBs).

Agha Beigi et al [9] proposed a retrofitting strategy equipped with GIB for the soft ground story that increases the lateral drift capacity without considerably increasing the lateral resistance, preventing the collapse and thus taking advantage of the isolating effect while reducing the P-Delta effect. This

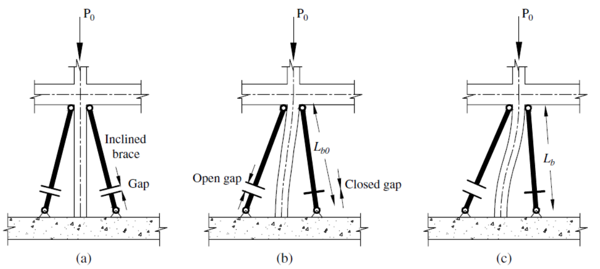

Figure 1: GIB system, (a) Initial condition,(b) Gap closed condition, (c) Ultimate condition(Agha Beigi et al [9])

detailed proposed model of GIB was described in a study of Salmon et al. [10] .

The system consists of an elastic inclined brace with a suitably selected gap element, as shown in Figure 1 (a). When the building is moved laterally, the lateral movement of the building results in lateral motion of the existing columns, as a result, an axial shortening is induced in the GIB, as illustrated in Figure 1(b).The gap within the GIB closes when the first-floor displacement surpasses a specific threshold, determined based on either P-Delta effects or the deformation limits of the first-floor columns. Upon closure of the gap, the GIB becomes operational, initiating the sharing of vertical and lateral loads with the existing columns, as depicted in the figure 1(c).

2. Experimental Study adopted for Numerical Validation

Agha Beigi et al [9]. introduced the concept of the Gapped-Inclined Bracing (GIB) system as a retrofitting method for soft-story buildings. To assess the effectiveness of this system, a comprehensive three-phase experimental program was conducted at the University of Toronto, led by Salmon et al. [10]. The first phase of the experiments involved testing a single brace, while phases II and III were dedicated to comparing the reverse cyclic response of two single-bay, single-story RC frames. These frames were designed to represent the ground floor of a soft-story structure and included a conventional frame and a GIB-retrofitted frame. The results from phases II and III of the experiment were employed for the purpose of 3D numerical validation. The simulation of the RC frames was carried out using DIANA, a nonlinear finite element analysis program.

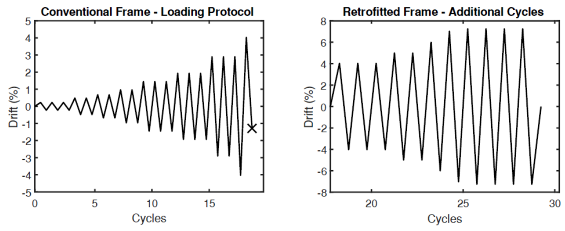

Figure 4: Loading conditions (Salmon J et al [10])

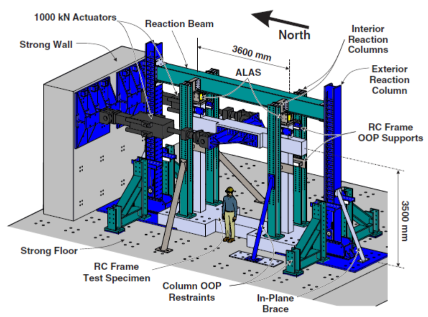

Figure 2: Experimental Study adopted for Numerical Validation(Salmon J et al [10])

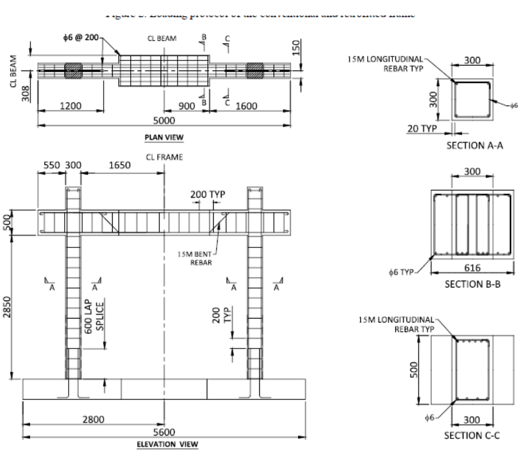

Figure 3: Reinforcement details of the experiment adopted for Numerical Validation(Salmon J et al [10])

3. Finite Element Modeling

Computational models were developed using the DIANA finite element software. A macro-modeling approach employing solid elements was utilized to closely mimic the experimental frames as shown in the figure 6. To align with the experiment, boundary conditions were set up to be as consistent as possible as decipted in figure 8. The reinforcement details adopted for numerical validation as in experiment is shown in figure 7 The choice of solid elements allowed for a more detailed representation of longitudinal and shear reinforcements. Employing 3D modeling within DIANA offered a more realistic and precise depiction of the system's behavior, potentially leading to improved designs and a better comprehension of the system. The GIBs were modeled as a regular truss element with gap incorporated in the stress-strain curve.GIB was modeled as a regular truss element with an equivalent area of a hollow cylindrical tube of size 168mm×13mm. That is, an External diameter of 168mm and thickness of 13mm respectively and length equal to length of GIB was assigned..

Various types of elements were used from the DIANA element library to develop the Finite Element models:

1. An 8-noded iso-parametric solid brick element (`HX24L`) that is used for stress- strain analysis to simulate the behavior of concrete and steel plates. It can suitably analyse the response of complex three-dimensional structures and can simulate failure modes [11].

2. A 2-noded 1D Truss-bar element (`L2TRU`) that can simulate only axial deformations and suitable for elements with hinge connection to model the GIBs [11]

3. The `BAR` element was used to simulate the longitudinal and shear reinforcements that are embedded within the concrete. [11]

A full restraint condition was applied at the base of the concrete foundation. The beam was designed to be robust to ensure uniform displacement without damage. This condition was maintained in the model using the 'multi-point tying' feature available in DIANA.

Regarding the applied loads, three distinct types were taken into account:

1. Self-weight of the frame was considered.

2. An axial load of 500 KN on each column, representing the weight of the story above the frame, was applied as a uniformly distributed surface load.

3. A displacement-controlled cyclic lateral load was applied at a node in the middle of the top beam with a load step of 1 mm and other nodes were connected to that node through tying.

Cyclic loading was applied as that of the experiment conducted by Salmon et al. [10] A total strain crack-based material model is employed for solid elements within frames. This model utilizes a smeared fracture approach with a rotating crack, which has proven to accurately predict the behavior of shear-dominated systems. Concrete for beam and column was assumed to follow constitutive laws; linear-exponential in tension that takes account of tensile strength and tensile fracture energy and linear-parabolic in compression that takes account of compressive strength and compressive fracture energy. For steel, Linear elastic isotropic model was adopted as these are assumed to be rigid and for simplified model of GIBs, a uni-axial non linear elastic model is adopted and gap is incorporated in stress-strain diagram.

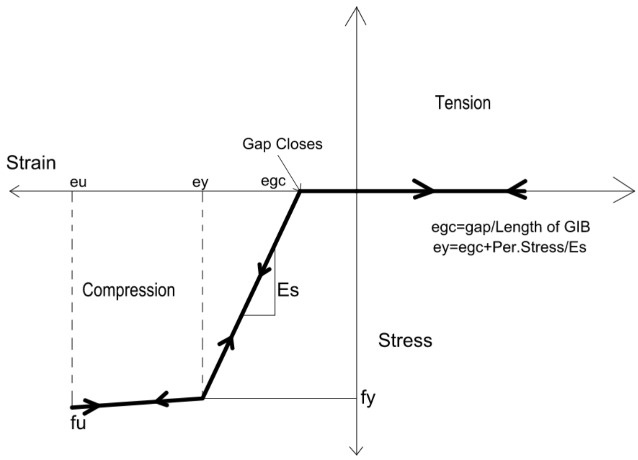

Figure 5: Simplified Gap element modeled in DIANA as compression-only element

The GIB element is designed as a compression-only element by eliminating stress on the tension side, focusing solely on the stress-strain curve in compression. To account for the gap in the stress-strain diagram, the distance of the gap in the GIB is converted into the corresponding strain (e.g., egc). This conversion is achieved by dividing the gap distance by the length of the GIB with a very small increment in compression stress. Following this conversion, the material is allowed to follow the typical stress-strain curve in compression, as depicted in the figure5.

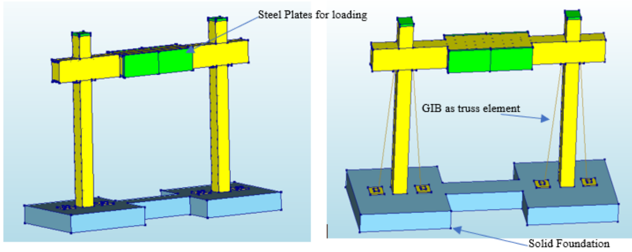

Figure 6: Geometry modeled in DIANA: (a) Conventional Frame; (b) Retrofitted frame

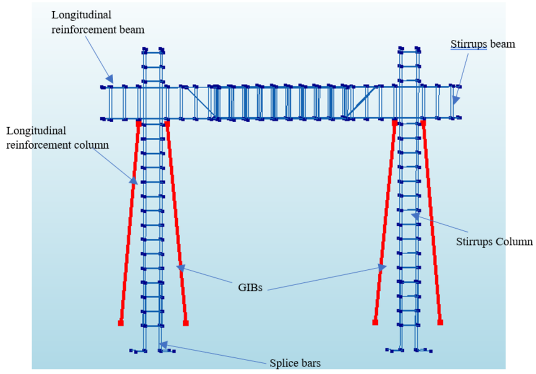

Figure 7: Reinforcement details of retrofitted frame(similar to conventional frame)

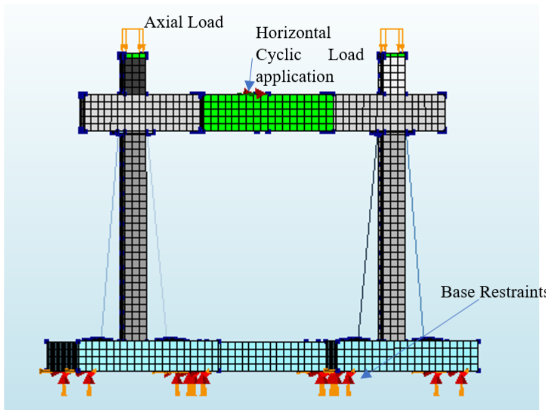

Figure 8: Meshing and Boundary conditions of Retrofitted Frame

Bond-slip reinforcement model for both longitudinal re-bars and stirrups was adopted . Truss bond-slip type reinforcement with Monti-Nuti plasticity model was taken as non-linear model. To replicate the actual condition, GIB is hinged in a steel plate at the top and bottom . The mesh size is kept as 100mm. Table 1 shows the material parameters used for numerical modeling.

4. Results and Discussion

The numerical models of conventional frame and retrofitted frame are subjected to reverse cyclic loading and hysteresis curve is compared with the experimental result. Figure 9 shows the comparison of envelope of hysteresis response of

Table 1: Material Parameters use for Numerical Validation of Phase II and Phase III experiment

Parameters	Concrete Foundation	Conventional Frame	Retrofitted Frame	Steel Plates	Reinforcement Bars	GIB Steel
Young's Modulus, E (MPa)	40,000	36,000	25,000	194,660	210,000	210,000
Poisson's Ratio, ν	0.2	0.2	0.2	0.3	0.3	0.3
Mass Density, ρ	2400	2400	2400	7850	7850	7850
Compressive Strength, f_c (MPa)	-	32	25	-	-	-
Tensile Strength, f_t (MPa)	-	3.02	2.565	-	-	-
Tensile Fracture Energy, G_t (N/mm)	-	0.151	0.136	-	-	-
Compressive Fracture Energy, G_c (N/mm)	-	40	34.5	-	-	-
Yield Strength, f_y (MPa)	-	-	-	-	600 MPa for 6mm, 400 MPa for 16mm diameter	60
Ultimate Strength, f_u (MPa)	-	-	-	-	-	61
Normal Stiffness Modulus, K_n (KN/mm^3)	-	-	-	-	1000 (for bond slip)	-
Shear Stiffness Modulus, K_s (KN/mm^3)	-	-	-	-	100 (for bond slip)	-

test and numerical model in DIANA of the Phase II conventional frame (bare frame only) from the experiment and numerical model. The peak values of the hysteresis response have been well captured by the numerical model indicating the suitability of the modeling approach.

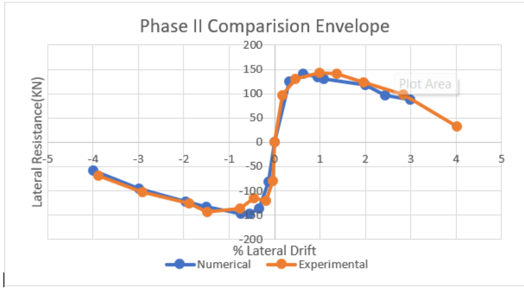

Figure 9: Envelope comparision of phase II

The area under the hysteresis loop in each cycle gives the numerical value of energy dissipated in each cycle. The energy dissipated at different drift level is found out through area covered by the loop at the certain drift level of the experiment and numerical model. Figure 10 shows the comparison of energy dissipation at different drift levels of the conventional frame and numerical model. It is seen that at lower lateral drift, energy dissipated by experimental and numerical model has not much difference. However, at higher drift level, the energy dissipation of the numerical model seems to be higher indicating more ductility in the numerical model.

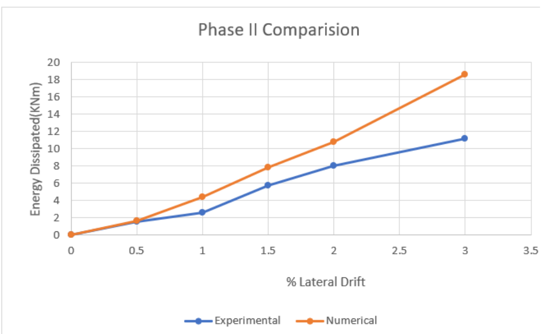

Figure 10: Energy Comparision of Phase II

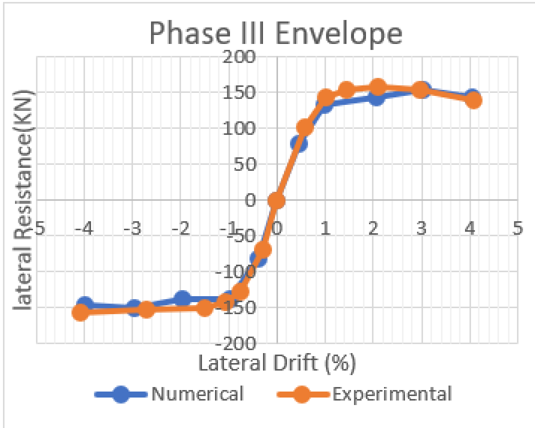

Figure 11: Envelope comparision of phase III

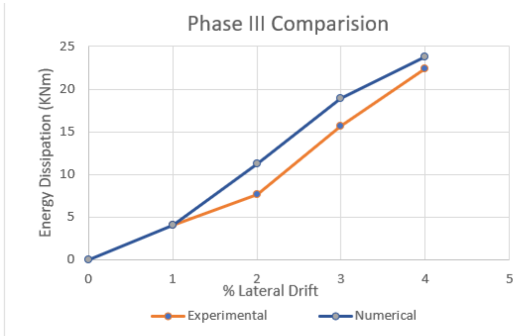

Figure 12: Energy comparision of phase III

Figure 11 shows the envelope comparison of peak strength of hysteresis response at different drift level of phase III experiment and numerical model of retrofitted frame. It is clear that peak values are well captured through numerical modelling indicating that the simplified model of GIB is able to represent actual behavior of GIBs. Figure 12 shows the energy dissipation comparison of the experiment and numerical model of phase III. Result shows they are in good agreement with each other. However, the energy dissipated in numerical model is comparatively higher indicating more ductility in numerical model. The discrepancy in the energy dissipation between the experimental result and numerical model at higher drift level may be because of non-linearities and of cracks that has been developed in the frame in the model that plays crucial role.

5. Conclusion

This paper presents the 3-D numerical validation of the experiment conducted by Salmon J et al [4]. The following conclusion has been drawn on the basis of the study:

• Effectiveness of the Numerical model:
The modeling approach appears suitable for simulating the cyclic behavior of the frame and the model used for GIB is simplified and suitable to simulate the behavior of the frame retrofitted with the GIBs. The peak response was accurately caught by the numerical models for both conventional and retrofitted frames. Moreover, the energy dissipation of the experiment and the numerical model shows less discrepancy indicating the material properties and their response to loading, including damping and non-linearity, are appropriately represented in the model. The numerical analyses have effectively reproduced the key phenomena observed in the experiments, demonstrating that the selected numerical modeling approach is suitable for future work.

References

[1] Nepal National Building Code NBC 105:2020. Seismic design of buildings in nepal. *Government of Nepal, Ministry of Urban Development*, 2020.

[2] Yukihiro Harada and Hiroshi Akiyama. Seismic design of flexible-stiff mixed frame with energy concentration. *Engineering Structures*, 1998.

[3] AK Chopra, DP Clough, and RW Clough. Earthquake resistance of buildings with a 'soft'first storey. *Earthquake Engineering & Structural Dynamics*, 1972.

[4] Dipti Ranjan Sahoo and Durgesh C Rai. Design and evaluation of seismic strengthening techniques for reinforced concrete frames with soft ground story. *Engineering structures*, 2013.

[5] Indian Standard Code IS. 2002 criteria for earthquake resistant design of structure. *Bureau of Indian Standards, New Delhi*, 1893.

[6] SI Israel Standard. 2004. design provisions for earthquake resistance of structures. the standards institution of israel, tel-aviv, israel, 1995.

[7] Peng Pan, Wei Li, Xin Nie, Kailai Deng, and Jiangbo Sun. Seismic performance of a reinforced concrete frame equipped with a double-stage yield buckling restrained brace. *The Structural Design of Tall and Special Buildings*, 2017.

[8] Hemant B Kaushik, Durgesh C Rai, and Sudhir K Jain. Effectiveness of some strengthening options for masonry-infilled rc frames with open first story. *Journal of structural engineering*, 2009.

[9] Hossein Agha Beigi, Constantin Christopoulos, Timothy Sullivan, and Gian Michele Calvi. Gapped-inclined braces for seismic retrofit of soft-story buildings. *Journal of Structural Engineering*, 2014.

[10] Jeffrey Salmon, Hossein Agha Beigi, and Constantin Christopoulos. Full-scale tests of gapped-inclined bracing system: seismic retrofit for soft-story buildings. *Journal of Structural Engineering*, 2019.

[11] Shun Chai. *Finite Element Analysis for Civil Engineering with DIANA Software*. Springer Nature, 2020.