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RETHINKING SOFT-STORY BUILDINGS: OVERVIEW OF DEVELOPMENT OF THE GIB CONCEPT

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Abstract

A novel gapped-inclined brace system (GIB) has been developed to enhance the seismic performance of soft-story buildings. The GIB system consists of a pinned brace and a gap element that is installed almost vertically at both sides of first story columns in existing buildings prone to a soft-story response. This intervention promotes the isolating benefits of the soft-story at the ground level to protect the upper floors of the structure from damage while greatly increasing the lateral deformation capacity of the first story and eliminating its propensity for collapse.

An overview of the system and its potential benefits to soft-story buildings is presented and a summary of the main steps of a design procedure for retrofitting soft-story buildings with this system is provided. The potential impact of the GIB system is then examined through a cost benefit study. The seismic response, the retrofit cost and the seismic repair cost of a six-story reinforced concrete (RC) frame retrofitted building using conventional approaches such as strengthening and stiffening of the soft-story is established and compared to the un-retrofitted existing building and the building retrofitted using the proposed GIB system.

Subsequently, selected results from an ongoing full-scale testing program carried out at the University of Toronto to confirm the behavior of the GIB system are summarized.

Keywords: Gapped Inclined Brace (GIB), Seismic retrofit, Soft-story, Cost benefit, Seismic resiliency

1. Introduction

Soft-story buildings such as ones incorporating pilotis are very common worldwide due to several architectural and socio-economical advantages they offer (parking, commercial space, storage and lobbies at the first floor of multi-story buildings) see Fig. 1.a. Post-earthquake surveys have shown that soft-story buildings have performed poorly in past earthquakes and have shown a propensity for collapse due to P-Delta effects (Fig. 1.b). As such they are considered as the most vulnerable portion of the building stock in many highly populated urban areas throughout the world. Soft-story buildings represented two thirds of the 46,000 units that were uninhabitable after the Northridge earthquake and a high percentage of the death toll was attributed to such buildings (Comerio 1995). From a total of 8.5 million deaths and almost $2.1 trillion in damages that have been reported all around the world for the past century, (Daniell *et al.* 2011), it could therefore be estimated that soft-story buildings have been responsible for millions of fatalities and several billions of dollars in losses in the past century alone.

Modern retrofitting procedures are intended to correct soft-stories by increasing their strength and stiffness. The increase in strength and stiffness reduces lateral deformations, and thus, reduces P-Delta effects acting on the first floor. Such retrofitting procedures are usually achieved by adding structural elements, such as structural walls or braces, at the first floor of soft-story buildings (Fig. 1.c). However, these strategies not only affect the architectural functionality of these buildings, but also greatly increase the total cost of the retrofit as the structure above the soft-story must be designed to resist the greater loads imparted by the retrofitted soft-story during an earthquake. In addition, the extent of the overall damage and losses in the retrofitted building after the earthquake may remain high primarily because of the damage induced to higher floors by the stiffening and strengthening of the soft-story.

Recently, Agha Beigi *et al* (2014) suggested the gapped-inclined brace (GIB) system, which consists of an elastic inclined brace with a carefully selected gap element (Fig. 1.d), to enhance the displacement capacity of a soft-story while not increasing its lateral resistance so as to protect floors above the soft-story. The proposed GIB is installed almost vertically at both sides of the column without inducing any force on the existing elements at this level (Fig. 2.a). During the lateral motion of the building, the lateral movement of the existing columns induces an axial shortening of the GIB, as illustrated in Fig. 1.e and Fig. 2.b. The gap inside the GIB closes once the first floor displacement exceeds a critical value. Once the gap is closed (Fig. 2.b and Fig. 2.c), the GIB activates and begins to share the vertical and the lateral load with the existing columns. As the lateral displacement increases, the axial load on the first story columns is increasingly reduced by the GIB so that, first, it counteracts P-Delta effects, and second, it increases the lateral deformation capacity of the first story columns, while not increasing the first story lateral resistance or stiffness. This will minimize the overall damage in the building by taking advantage of the isolation provided by the soft-story to the rest of the structure located above (Agha Beigi el al, 2015).

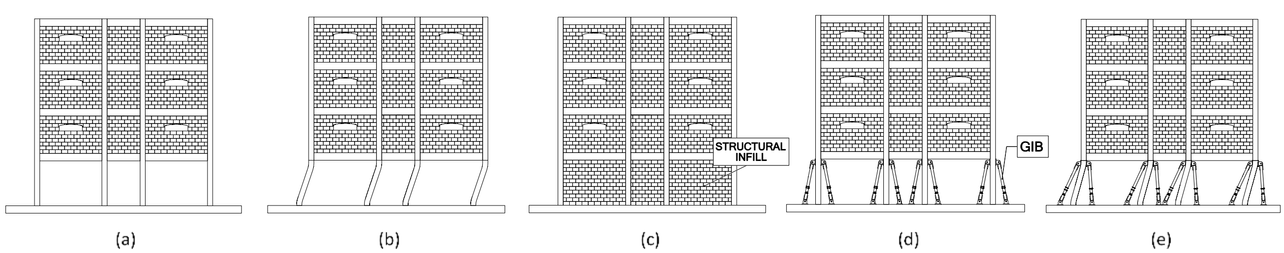


Fig. 1 – a) soft first story buildings, b) typical seismic damage to soft story buildings, c) common retrofit strategies , d) proposed GIB system) , e) response of the retrofitted building using GIB system during earthquake

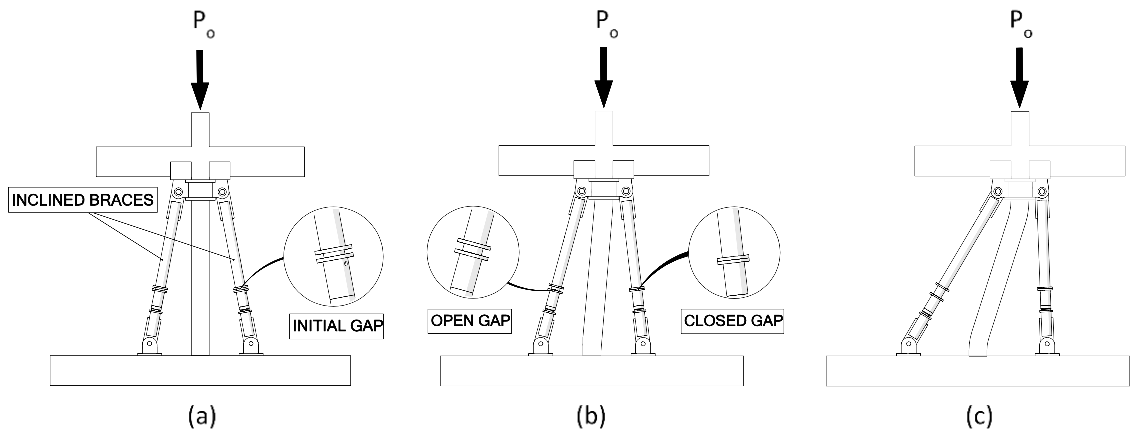


Fig. 2 – Gapped-Inclined Brace (GIB) system to the existing column a) initial condition b) closing gap condition c) ultimate condition

In this paper, the design of the GIB is first outlined. Then, an existing six-story reinforced concrete frame building is taken as a benchmark and its seismic response and cost-benefit analysis are compared for three scenarios: un-retrofitted; conventional retrofits, such as stiffening and strengthening the soft-story; and retrofitting with the GIB system. Lastly, selected results from the full-scale testing program of the GIB system, currently underway at the University of Toronto as part of a full-scale concept validation project, are also summarized.

2. Overview of proposed design procedure for retrofits using the GIB system

The design procedure of the GIB system for each column consists of five main steps: the first two steps are aimed at estimating the demand forces on the GIB to ensure that the lateral deformation capacity of the existing RC columns is increased up to the target displacement. To this end, a degraded-capacity (DC) curve is determined by plotting the envelope of force-displacement capacity curves for the existing ground story columns resulting from analyses in which P-delta effects are considered. An "effective" axial force P_{eff} is then determined as a function of lateral drift that will minimize P-Delta effects and maximize the lateral drift capacity of the columns (Fig. 3.a) by relieving the columns of their axial load as they are deflecting laterally. To determine P_{eff} for each column, the maximum lateral drift capacity of that column is plotted versus the expected range of axial load. Subsequently, the axial load that corresponds to the ultimate drift capacity of each column P_u is determined.

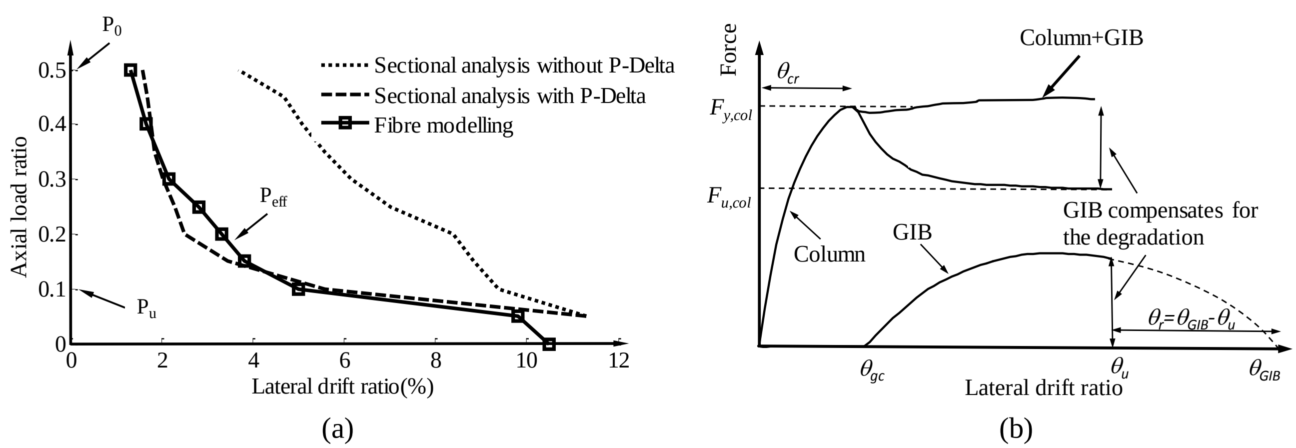


Fig. 3 – Parameters and graphs used for the GIB design: a) $P_{eff,}$ b) DC curve

The three remaining steps are aimed at setting the design parameters of the GIB to achieve this targeted effective force when the building is deforming laterally. The initial angle of the GIB, θ_{GIB} controls the lateral resistance, and consequently, lateral forces that are transferred to the upper floors. The gap distance Δ_{gap} is set considering the point at which the lateral resistance of the existing column starts to decrease (Fig. 3.b). The inclined brace of the GIB system also needs to be checked to ensure that it has sufficient resistance against buckling and against the maximum forces imparted to the system. More information about the detailed design steps of the GIB system can be found in Agha Beigi et al (2014).

3. Example Building studied

A case study comparing the seismic response of a six-story planar structure encompassing eight retrofitting alternatives was investigated; the eight alternatives, referred to as variants, are shown in Table 1.

The planar frame configuration that was considered, which is representative of typical buildings that have been designed in Italy (and other parts of the world) during the 1950 and 1970s, was initially studied by Galli (2006). As such, the structural elements were designed for gravity loads without specific consideration for seismic loading. The structure is part of a frame system formed by a series of parallel frames spaced at a distance of 4.5 m between the centerlines of the frames. The first floor height is 2.75 m, while the other stories have a height of 3.00 m. The frame consists of two 4.5 m long identical exterior bays and one interior 2 m bay.

More information of the building and the design parameters of the GIB system for each variant can be found in Agha Beigi et al (2016).

Table 1. Case study variants

Variant No.	Variant Name	Description
1	SS	Soft-story Variant
2	FI	Full Infill Variant (Similar to SS but infill continues to the ground floor)
3	GIB-I	GIB Variant Configuration 1 (Fig. 4.a)
4	GIB-II	GIB Variant Configuration 2 (Fig. 4.b)
5	GIB-III	GIB Variant Configuration 3 (Fig. 4.c)
6	GIB-G-0.5	Similar to GIB III, gap distance is halved
7	GIB-G-2	Similar to GIB III, gap distance is doubled
8	GIB-G-0	Similar to GIB III, gap distance is zero

4. Loss estimation results

To estimate the likely losses for this case study building, the methodology proposed by Ramirez and Miranda (2009) was adopted in this study. This methodology, which stems from the Pacific Earthquake Engineering Research PEER framework (Porter, K. A. 2003a), studied and developed by other researchers involves four basic analysis stages: ground motion hazard assessment for the site, structural response of the building for a given hazard level, quantification of damage of building components as a function of the structural response, and estimation of repair costs associated with different damage levels. Site specific seismic hazard was not used in this study. Instead, the intent was to provide a general assessment of likely losses for a range of seismic intensities that could be associated with different probabilities of exceedance (depending on the seismicity of the actual site in question). As such, the seismic repair cost of each variant was calculated using the last three steps of this loss assessment procedure. Detailed information on the loss estimation procedure and the cost benefit study is described in Agha Beigi et al (2016).

Fig. shows the collapse fragility curves and the total repair-to-replacement cost (RRC) ratios of variants SS, FI, GIB-I, GIB-II and GIB-III for all intensity levels. While the collapse potential of the FI variant is less than that of the SS variant (comparing the solid line to the dashed line in Fig. .a), it is greater than the collapse potential of all GIB variants (GIB-I, GIB-II and GIB-III). A similar trend can be seen for the total repair cost (Fig. .b): over almost all intensity levels (0.1g to 0.6g) the RRC of the FI variant is less than that of the SS variant, but is greater than the values obtained for all GIB variants. As expected, the collapse potential of the GIB-III variant is more than that of the GIB-I and GIB-II variants because the GIBs are located on one side of each column only, and thus, the lateral capacity of the GIB-III is less than that of the GIB-I and GIB-II. For the same reason, the collapse potential of the GIB-II is slightly more than that of the GIB-I.

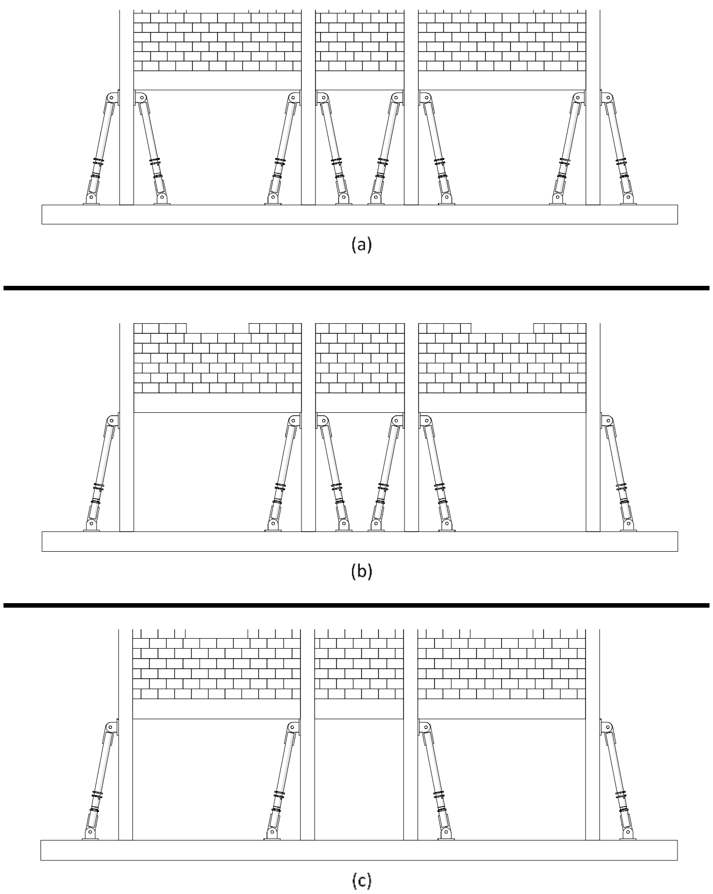


Fig. 4 – Case study variants: a) GIB-I variant, b) GIB-II variant, c) GIB-III variant

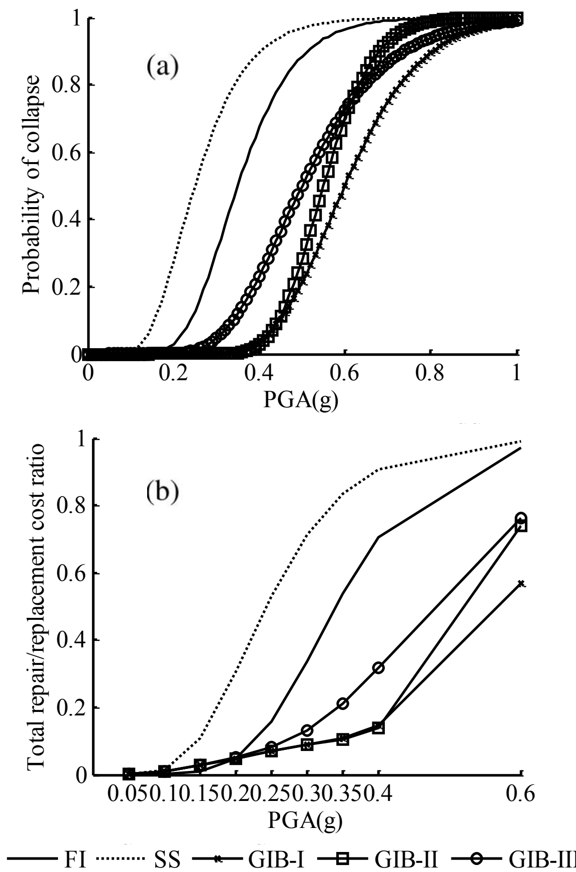


Fig. 5 – Loss estimation results for all variants

5. Cost-benefit study

To calculate the cost-effectiveness of different retrofitting schemes, a similar approach to that of Liel and Deierlein (2013) is used without considering human losses and down time. To this end, the repair cost of all the variants were first obtained, as described in the previous sections. Subsequently, the retrofit cost-benefit values, (RCB) for all the retrofit variants were calculated as the difference between the repair costs expected for the original and retrofitted solutions, minus the retrofit cost, using Eq.1:

$$\mathrm{RCB} = (\mathrm{RRC}_{\mathrm{SS}} - \mathrm{RRC}) - \mathrm{RTRC} \tag{1}$$

where, RTRC is the retrofit cost expressed as a ratio of the replacement cost (computed in Column 5 in Table 2), RRC is the repair cost ratio of the retrofitted variants and RRC_{SS} is the repair cost ratio computed for the SS variant. The RTRC using traditional retrofit strategies typically cost between 25%-40% of the value of the building (Mulargia, F. and Geller 2003a). However, for the calculation of RTRC of the FI variant, two values of 30% (high cost, assuming retrofit works over all stories, indicated as FI-high cost) and 10% (low cost, assuming retrofit work at the ground story only, indicated as FI-low cost) were considered. When using the GIB system on all columns the RTRC is estimated as 10%, which is assumed based on engineering cost estimates for the realization of GIB systems. The RTRC using GIB-III could be estimated as half of that of GIB-I (RTRC=0.05) because the number of GIBs would be halved. For the same reason, the RTRC of the GIB-II is estimated as 0.075.

The repair-replacement cost RRC ratio and the retrofit cost benefit (RCB) of all the variants at the three intensity levels of 0.20g, 0.40g and 0.60g are shown in in Table 2. Overall, this table indicates that the GIB system could be a very cost-effective solution compared to the conventional approaches as it can significantly reduce the seismic repair cost of the building, i.e. up to 57% with a cost benefit of up to 65%. The last three columns of Table 2 indicate that any one of the GIB scenarios could be the most cost effective retrofit strategy depending on the seismic hazard level.

The FI-high cost scenario could not be a cost effective solution because the retrofit expense could be even more than the benefit attained when the building is retrofitted (the RCB is estimated as -6% (29-35=6). However, life safety is improved with the traditional retrofit solution as the median collapse intensity increased from 0.25g to 0.37g. Using the FI-low cost scenario, the RCB is improved by 16%, but it is still smaller than that of the GIB scenarios.

Table 2. Loss estimation results of all variants and their retrofit cost benefit

		Collapse fragility parameters		Retrofit cost as ratio of replacement cost	Repair cost as ratio of replacement cost			Retrofit cost-benefit value as ratio of replacement cost		
Var. No.	Variant Name	x_m g	β	RTRC	RRC			RCB		
					0.20g	0.40g	0.60g	0.20g	0.35g	0.60g
1	SS	0.25	0.37		0.31	0.83	0.99			
2	FI-high cost	0.35	0.3	0.3	0.05	0.54	0.97	-0.04	-0.01	-0.28
	FI-low cost			0.1				0.16	0.19	-0.08
3	GIB-I	**0.60**	0.23	0.10	0.05	0.11	**0.57**	0.16	0.62	**0.32**
4	GIB-II	0.55	**0.17**	0.08	0.05	**0.10**	0.74	0.19	**0.65**	0.17
5	GIB-III	0.50	0.30	**0.05**	0.05	0.21	0.76	**0.21**	0.57	0.18
6	GIB-G-0.5	0.50	0.29	0.10	0.05	0.20	0.77	0.16	0.53	0.12
7	GIB-G-2	0.50	0.26	0.10	0.04	0.18	0.79	0.17	0.55	0.10
8	GIB-G-0	0.50	0.23	0.10	0.04	0.15	0.84	0.17	0.58	0.05
	Max/Min	0.6	0.17	0.05	0.04	0.10	0.57	0.21	0.65	0.32

* The bold value indicates the most optimum scenarios (max or min value in each column of the table)

At the 0.4g intensity level, the RRC of the GIB-I and GIB-II are almost similar. For GIB-III, the RRC was calculated as 0.21, which is almost double the values obtained for GIB-I and GIB-II. At the lower intensity level of 0.20g, the repair cost of the SS variant is almost one third of its replacement cost (RRC=0.31). Using the GIB system with different configurations results in a similar effect on the reduction of the repair cost as adding infills (RRC=0.05). Using the same aforementioned methodology, the GIB-III would result in the lowest cost of retrofit (the number of GIBs are halved compared to GIB-I).

At intensity levels as high as 0.60g, the repair cost of the SS variant is almost equal to its replacement cost (RRC=0.99). Strengthening the ground story (FI case) did not improve the repair cost (compare 0.99 to 0.97 for FI variant). However, using the GIB system, the repair cost of the SS variant is reduced to 0.57. At the intensity level of 0.60g, the variant GIB-I represents the most cost effective seismic retrofit scenario with a retrofit benefit higher than those from both traditional retrofit solutions (FI-high cost and FI-low cost).

It should be noted that indirect losses such as human losses and downtime, which were not included in this study, could also affect the cost benefit results. When using traditional retrofit strategies, the building has to be evacuated for several months or even years for both retrofit and repair work, forcing the residents to move elsewhere. For multi-story residential buildings, there could be additional challenges since residents at a given floor may have constraints (e.g. occupation, time) that could differ from residents at other floors, and thus, the impact of the retrofit on their activities could be different. Using the GIB system, because all the retrofit and the major parts of the repair work are carried out only at the first floor of such multistory buildings, the above interruptions (evacuation of residents, loss of business, etc.) could be reduced significantly. It is recommended that the impact of indirect losses on the effectiveness of using GIB systems be investigated in more detail as part of a future study.

6. Experimental Validation program for the GIB System and selected results

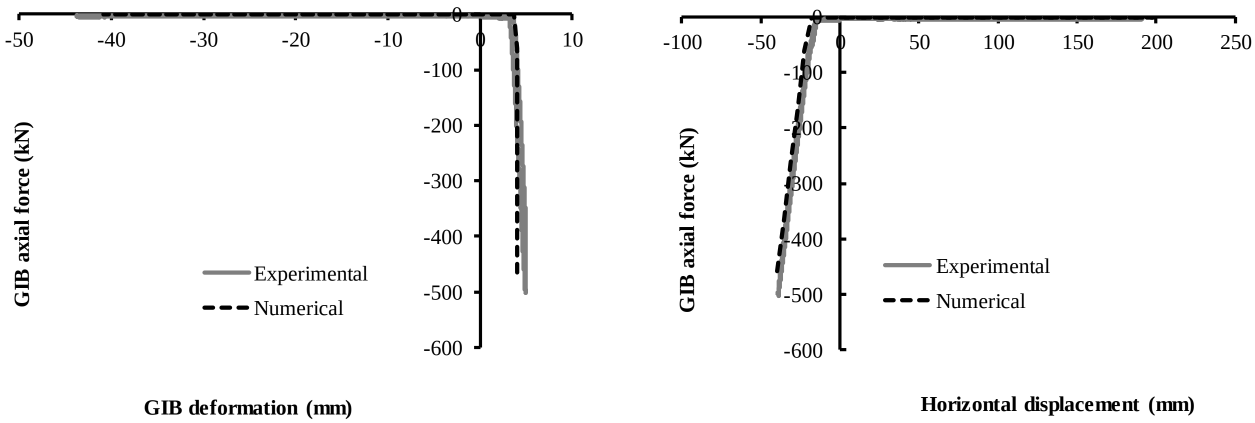
An experimental program is currently underway at the University of Toronto to validate the performance of the GIB retrofit concept in full-scale.

In Phase I of this program, the behavior of a single full-scale GIB assembly to quasi-static lateral loading was first studied. The test setup, as shown in Fig. 6, consisted of a supporting frame, hydraulic actuators, reaction wall, and GIB specimen. The hydraulic actuators were connected to a horizontal supporting beam and were used to create relative displacement between the horizontal beam and the strong floor foundation. With the GIB attached to the horizontal beam, the specimen is loaded similarly to its practical application, i.e. the relative displacement between the horizontal beam and the strong floor is analogous to that of the first floor and foundation of an existing structure. The design of the test frame permitted in-plane lateral displacement while preventing out-of-plane movement of the GIB.

The GIB was positioned with an initial angle of 86 degrees relative to horizontal and pin connected to the horizontal beam. The initial gap opening was set to 3.5 mm, which was achieved with precision by adjusting the threaded male component inside the female component. The threaded component which enabled an adjustment of the gap distance also allowed multiple tests to be carried out for various gap distances.

Fig. 4.a shows the axial force-axial deformation curve under the monotonic loading protocol. The axial load is calculated using the average of the strain gauges at eight locations on the GIB surface. The axial deformation was calculated using two longitudinal LVDTs installed on the East and West side of the GIB. As predicted, the relation between the axial load-axial deformation is linear. Fig. 4.b shows the relationship between the axial force in the GIB and the lateral displacement under the monotonic loading. The axial force in the GIB increases immediately once all sides of the gap are closed. When the lateral displacement at the top of the blue beam reached 35 mm, the axial force in the GIB increased to up to almost 500 kN. At this lateral displacement, the horizontal component of the GIB axial force was 21 kN, which was much less than its vertical component, i.e. 460 kN.

The experimental results were also compared to numerical analyses. The test setup was analyzed using a fibre model in SeismoStruct. In this model, the supporting columns and the supporting beam were modeled using frame elements. The base of the columns were modelled as pin connections. To prevent in-plane lateral resistance of the test frame, the rotational degree of freedom at both ends of the beam were released. The GIB and gap were modeled as a truss element and a gap element, respectively. Fig. 4 shows that numerical analyses predicted the experimental results well.



(a) (b)

Fig. 4 – GIB axial force, gap =3.5mm

The above test was repeated for two more gap distances of 8 mm and 25 mm. Fig. 5 compares the response of the GIB for different gap distances. As the gap distances increase, the axial force in the GIB initiates at a larger frame displacement. For a gap of 8 mm, the frame was pushed until the axial force in the GIB reached 500 kN. With a gap of 25 mm, the frame was pushed until the GIB reached a vertical position. At this stage, the axial force in the GIB reached 600kN. Similar to a gap of 3.5 mm case, for these two gap distances, it was observed that the results from the experimental analyses were in good agreement with those obtained from the numerical analyses.

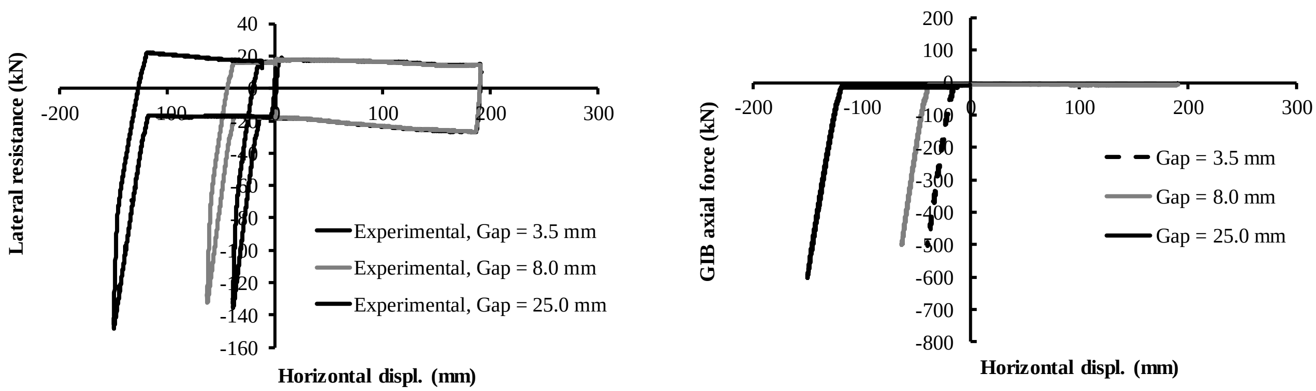


Fig. 5 – Effect of gap distance on the GIB response

6. Ongoing Frame test validations

The next phases of the experimental program were designed to compare the cyclic response of two identical single-story reinforced concrete frames, as shown in Fig. 7. To select the frame prototype and test frame, a number of detailed numerical analyses were carried out. The test frame was then selected such that its seismic response would be representative of that of the first floor of the frame prototype.

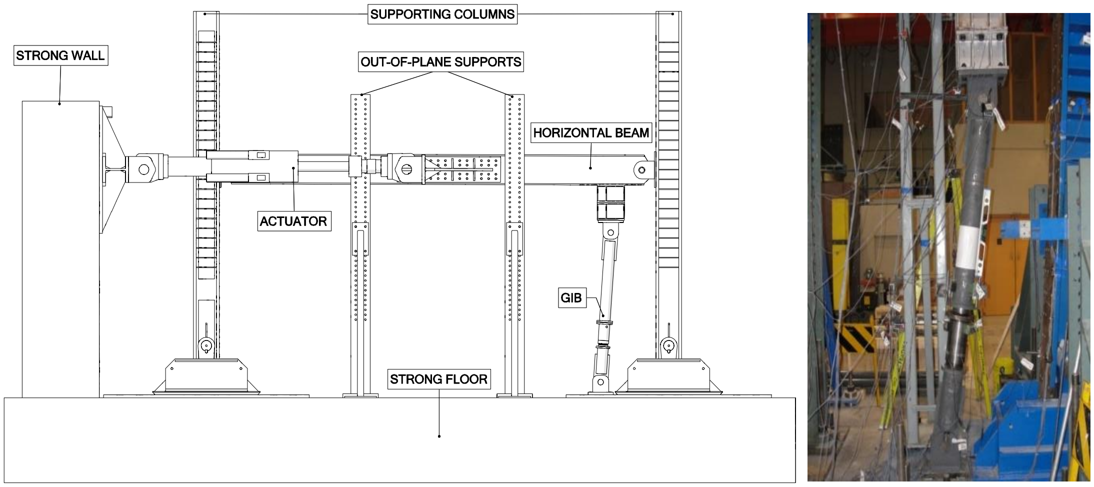


Fig. 6 – Phase I Test Setup: (a) Schematic Drawing; (b) Test Photo

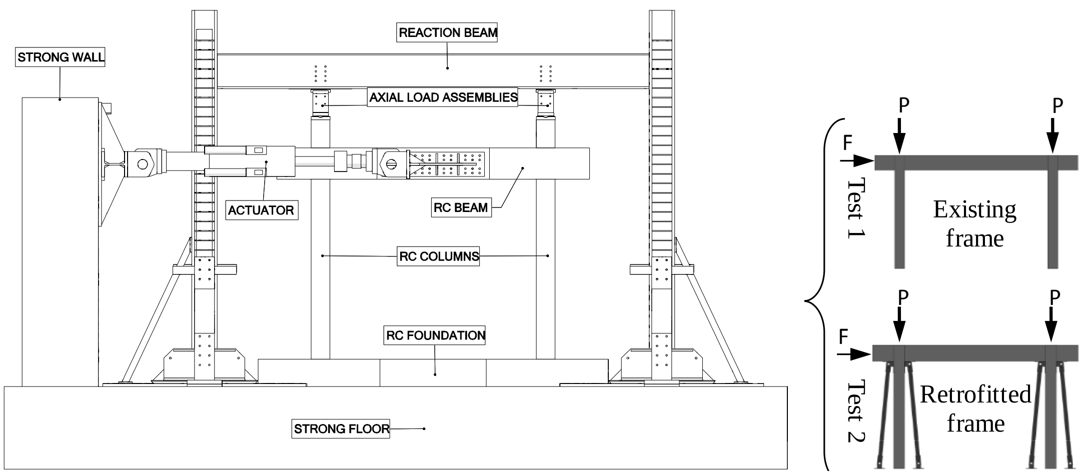


Fig. 7 – Full scale test of an existing RC frame and retrofitted RC frame

The conventional soft-storey frame was tested in the Structural Testing Facility at the University of Toronto and confirmed the expected soft storey mechanism response and rapid deterioration of strength at low drift levels. The retrofitted frame is scheduled to be tested under the same loading conditions. For this second test, to emulate the in-situ installation conditions and restrictions encountered in real practice during the retrofit of existing RC frames, the installation of the GIB will be carried out in the laboratory on a prefabricated as-built RC frame.

7. Conclusion

In this overview paper, the results from the cost benefit analysis suggested that, over all the intensity levels, if the existing soft-story frame is retrofitted using the GIB system, the cost benefit is far greater (40% to 70% greater) than a traditional retrofit scenario (FI variant). This occurs because both the retrofit cost and the repair cost using the GIB system is expected to be less than traditional solutions that aim to strengthen the soft-story level.

The GIB system was validated experimentally under a quasi-static loading regime. The preliminary test results showed that the global performance of the GIB system is similar to what was numerically predicted. The GIB does not provide any lateral resistance when the gap opens. Once the gap closes, the axial load in the GIB increases rapidly without significant increase in the lateral resistance of the exiting test frame. With the results observed from this phase of the testing, the design considerations of the GIB system were further calibrated. Testing of full-scale RC frames retrofitted with the GIB system are currently ongoing to validate the overall system behaviour.

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