NUMERICAL MODELLING OF GRAVITY-LOAD-DESIGNED REINFORCED CONCRETE COMPONENTS

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Abstract

Much of the existing building stock in earthquake-prone regions was constructed before the advent of seismic design in building codes. These structures, commonly referred to as gravity-load-designed (GLD) buildings possess low strength and ductility capacities, which has led to their poor performance in past earthquakes. Many of these structures require seismic upgrades or retrofits. An accurate assessment of GLD structures and components is a necessary first step for properly developing retrofit strategies. This paper presents a series of numerical validation studies of GLD reinforced concrete (RC) components using ATENA, a nonlinear finite-element-analysis program specially designed for reinforced and plain concrete. Numerical models were created to simulate three beam-column (BC) joints and two RC soft-storey frames. The BC joints represent interior, exterior, and corner joints. The RC frames were tested to validate the gapped-inclined bracing (GIB) system, which is a seismic retrofit for soft-storey buildings. The progression of the numerical models is explained for each component, starting with the default properties determined by the program. Some of the capabilities and limitations of ATENA are illustrated in this paper. It was found in all cases that ATENA captured the correct failure mode and peak strengths of the specimens. In some cases, strength degradation was more severe in the numerical model, which may be attributed to the fact that the shear and bending stiffness of the rebar, which can provide additional confinement to BC joints, is neglected.

Keywords: ATENA, Nonlinear Analysis, Gravity-Load-Designed, RC Beam-Column Joints, GIB

1. Introduction

Before the advent of seismic design in building codes, many seismic-prone regions designed structures considering only gravity loading, referred to herein as gravity-load designed (GLD) [1, 2, 3, 4, 5, 6]. GLD deficiencies include low longitudinal and transverse reinforcement ratios; insufficient detailing of reinforcement, especially with regard to anchoring of transverse reinforcement; poor quality of materials, with low concrete strengths and smooth-bar reinforcement; inadequate confinement in the beam-column (BC) joints; and beam longitudinal reinforcement terminated in the BC joint, which are susceptible to pull-out failures [5, 7]. Due to the poor seismic detailing, GLD structures have a history of poor seismic performance, as illustrated in numerous earthquake reconnaissance reports [3, 8].

To determine a retrofit strategy, an accurate assessment of GLD components is necessary. This paper presents a procedure for modelling seismically deficient, or GLD, RC components using ATENA. Calibration is presented as a progression of modelling choices, starting with the initial response considering only the material properties and evolving into more sophisticated models that include shrinkage strain and/or bond slip of the rebar reinforcement. Five experimental specimens were analyzed: (1) an interior BC joint; (2) an exterior BC joint; (3) a corner BC joint; (4) a soft-storey RC frame; and (5) a soft-storey RC frame retrofitted with the gapped-incline-bracing (GIB) system [9].

It was found that ATENA captures the failure mode and peak strength well. The accuracy relating to stiffness and peak strength were improved when shrinkage was modelled before applying any loads. If smooth-bar reinforcement was used, modelling the bond-slip law showed a significant improvement in results. Usually, post-peak degradation was more severe in the numerical model than observed experimentally. One potential source for this degradation stems from the method for modelling the rebar, which is done using truss elements that neglects the shear and bending stiffness of the steel reinforcement.

2. Modelling Assumptions

ATENA is a nonlinear finite-element-analysis program for reinforced concrete (RC) structures. The program may be used in 1D; 2D, with either plane strain or plane stress elements; or in 3D with solid or shell elements. In the program, an incremental tangent-stiffness approach is solved using a Newton-Raphson, modified Newton-Raphson, or Arc-Length solution scheme. A fracture-plastic concrete constitutive modelling is followed. The fracture model, used for tensile response, employs an orthotropic smeared crack model and crack band theory [10] with a nonlinear softening response. A Rankine failure criterion is used, and the smeared cracks can be modelled as rotating or fixed. The hardening/softening laws for concrete in compression follow the Menetrey-Willam plasticity surface [11]. To achieve mesh independent models, the crack band theory using fracture energy has been applied to the cracking response and adapted to simulate a fictitious band for concrete crushing. For further information, see [12].

ATENA-GiD 3D was used for all analyses described herein; some of the analyses were first performed using a 2D plane stress formulation, but it was found that the out-of-plane confinement, which stems from the connecting elements (e.g. the foundation for a cantilever column) was not accounted for properly. The NonlinearCementitious2 material was used for the concrete and discrete truss-bar elements were used for the reinforcement. The cyclic reinforcement models were used in all analyses described below with the program-default values for the Baushinger effect and Menegotto-Pinto response. In all cases, a mesh sensitivity study was performed. All other modelling assumptions are described in the relevant sections below.

3. Modelling Beam-Column Joints

Gravity-load-designed BC joints have been identified as particularly vulnerable to seismic loading. Experimental campaigns over the last 20 years have focussed on understanding the structural response and developing retrofits for poorly designed joints [2][13][14]. This section outlines a modelling method for an interior joint, an exterior joint, and a corner joint.

3.1 Interior BC Joint

Hakuto, Park, and Tanaka (2000) tested a series of seismically deficient BC joints, representative of pre-1970s construction in New Zealand [2]. Specimen O1 from the experimental programme was modelled; the interior joint has a strong beam, weak column design with no confining reinforcement in the joint core. The reinforcement details and test setup are shown in Fig. 1 (a) and (b), respectively. These specimens were tested without axial load and reversed cyclic displacements was applied at the top of the column.

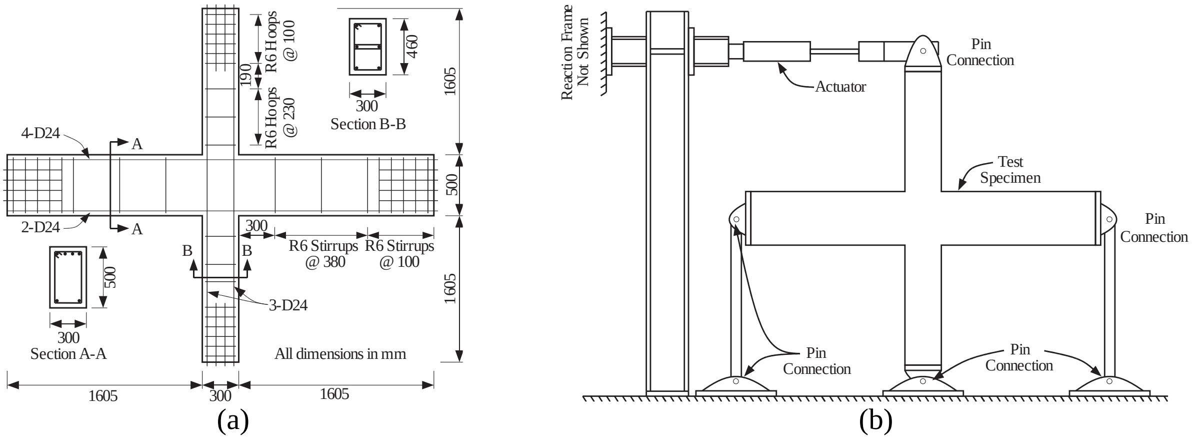


Fig. 1 – Interior Joint: (a) Geometry and reinforcement details; and (b) Test setup (adapted from [2])

The material properties that were available were input while the others were program calculated, which follows CEB-FIP model code 90 [15], see [11] for details.

The ATENA model and mesh that were developed for this test specimens are shown in Fig. 2 (a) and (b), respectively; half the structure, cut through midline of the thickness, was modelled taking advantage of the symmetric boundary condition. The bottom of the column was restrained against translation in all direction, while remaining free to rotate. The ends of the beam were free to translate laterally (x-direction) but restrained in the vertical direction (z-direction). The symmetric plane was restrained in the y-direction.

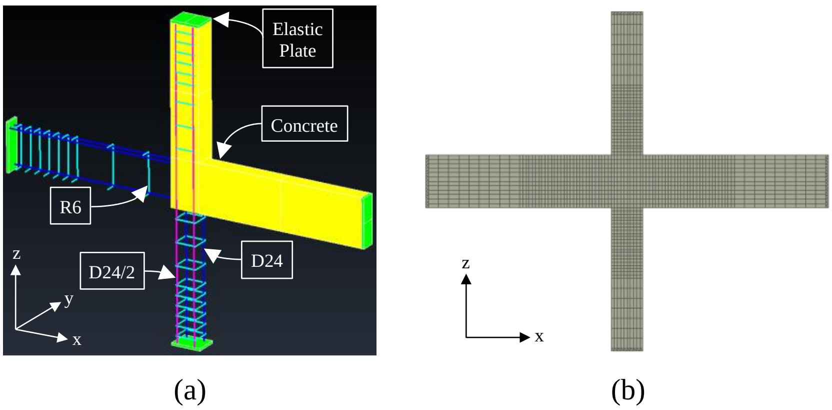
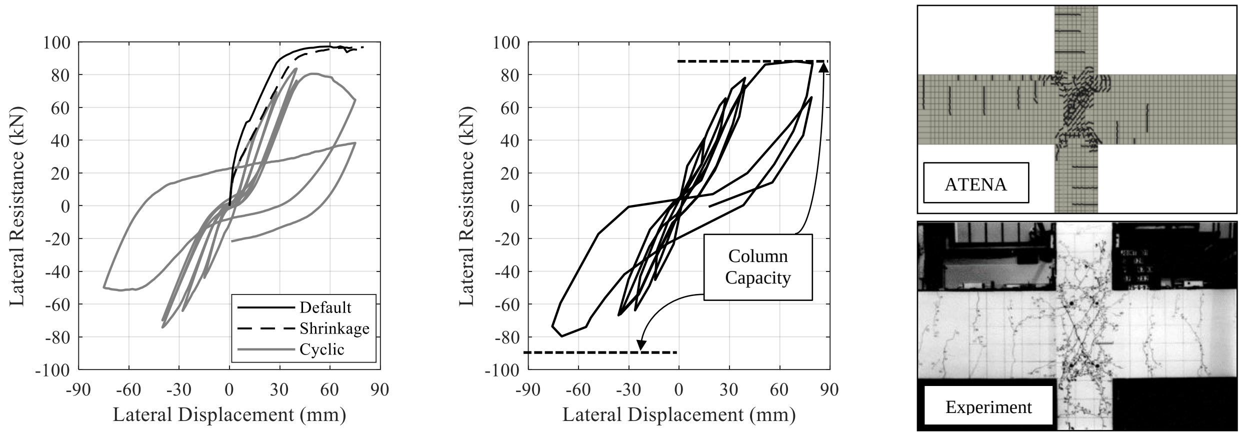


Fig. 2 - ATENA model of specimen O1 (a) Model and (b) Mesh

A pushover and reversed cyclic analysis (not shown here) of the default model was compared to the experimental results. It was found that the peak strength and failure mode were well captured; however, the initial stiffness was higher in the model than observed experimentally. The effective stiffness of the model was improved by including shrinkage strain; a shrinkage strain of -300 mm/km was applied in all directions, which was taken from [15] assuming roughly 75 days between casting and testing; the number of days between casting and testing was estimated, as this was not provided by the authors. Care was taken to avoid spurious cracking at the boundaries between the elastic loading plates and the concrete elements. The pushover and cyclic response of the updated model (i.e. including shrinkage) captured more accurately the force-deformation response of the joint. These results are illustrated in Fig. 3. The ATENA results (Fig. 3 (a)) show the pushover response for both the default and updated model, along with the cyclic response of the updated model; the updated results compare well to the experiments (Fig. 3 (b)). The crack patterns between the experiments and numerical model showed a concentration of cracking in the BC joint (Fig. 3 (c)).



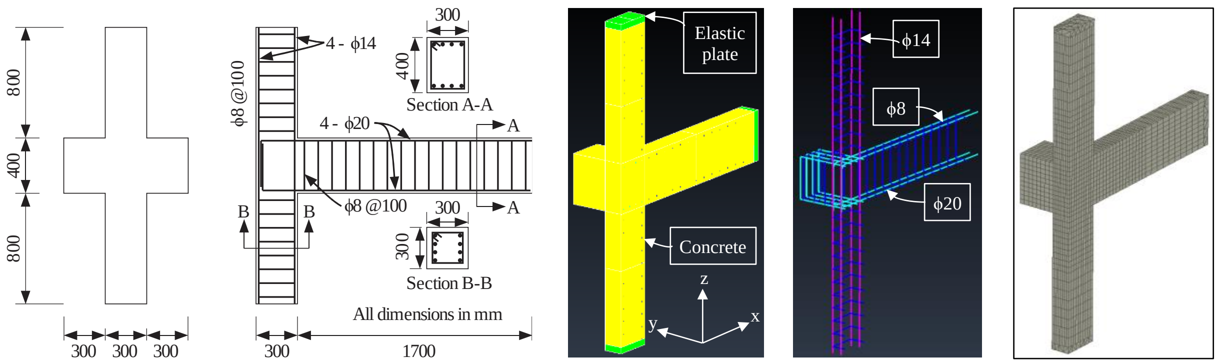
(a) (b) (c)

Fig. 3 – Results: (a) ATENA force-displacement; (b) Experimental force-displacement [2]; (c) ATENA cracking pattern; and (d) Experimental cracking pattern [2]

3.2 Exterior BC Joint

De Vita, et al. (2017) tested a series of exterior RC BC joints, representative of GLD structures, to determine the effectiveness of different glass- and carbon-fiber reinforced polymers wraps as a retrofitting technique [13]. One of the conventional specimens (specimen J_{k11}) was modelled in ATENA. The geometry and reinforcing details of the joint are shown in Fig. 4 (a). The joints were subjected to a constant axial load of 295 kN, and a reversed cyclic displacement was applied at the end of the beam. No loading was applied to the transverse beam stubs; see [13] for further details.

The material, reinforcement layout, and mesh of the ATENA model that was developed for this specimen are shown in Fig. 4 (b). Again, a symmetric boundary condition was used for computational efficiency. Pin and roller connections were applied, respectively, at the base and top of the column. The surface of the symmetric plane was restrained in the y-direction. The steel plates were fixed to the ends of the concrete elements; however, this was deemed to have a negligible effect on the response of the system, as the nonlinearity was concentrated close to the BC joint.

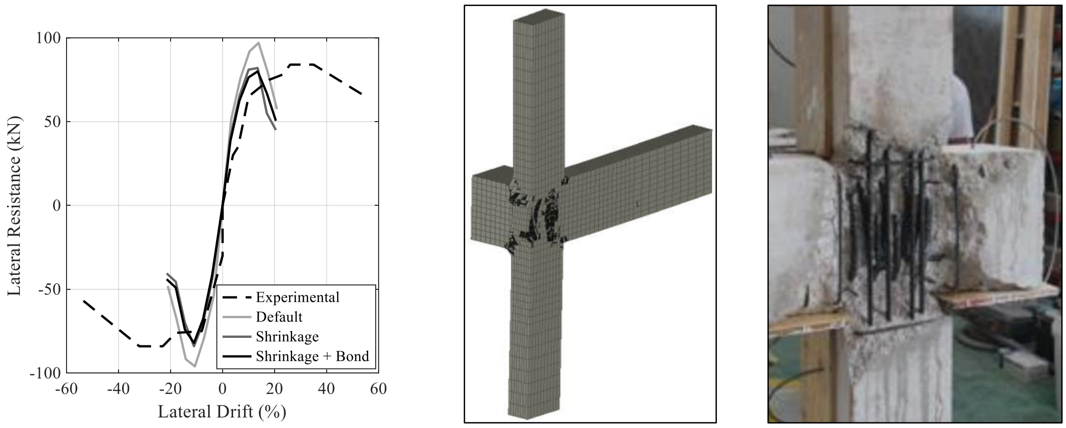


(a) (b)

Fig. 4 - Exterior RC: (a) Reinforcement details (adapted from [13]) and (b) ATENA model details

One cycle at each experimental drift amplitude was analyzed in ATENA. Incremental changes to the model were made and are compared in Fig. 5 (a); the envelopes from the reversed cyclic responses are compared to that from the experiment. The shear failure in the joint was well captured in each case. The stiffness of the default model was well represented in the negative loading direction but stiffer in the positive loading direction. The peak strength in both loading directions was slightly overestimated. Again, a shrinkage strain of -300 mm/km was applied in all directions, and with shrinkage strain, the peak resistance of the model was more accurately captured; however, the effective stiffness in the positive loading direction did not show significant improvement. Bond-slip may also play a role in stiffness and peak strength of the experimental specimen. The CEB-FIB model code 1990 [15] response, including the reversed cyclic response, was used in the model with “all other conditions”; the response was essentially unaffected.

The post-peak response from all models was greatly underestimated. One of the contributing factors was believed to be the method used to model the longitudinal reinforcement and the way it was anchored in the BC joint. Rebar is commonly modelled using truss elements, which carry only axial forces and neglect the shear and bending stiffness of the steel reinforcement. Initial attempts (not shown here) had the rebar anchored at a single point within the joint. However, a pull-out failure or shearing of the concrete elements adjacent the rebar was observed and controlled the response of the model; the results were also sensitive to meshing. With a more refined mesh, pull-out failure of the rebar initiated earlier. Modelling the arc in the 90-degree bend and meshing with 10 elements over the curved rebar section improved the results slightly, but care must be taken to ensure that the failure mode is not a spurious one. Other researchers have used beam elements embedded in the concrete, using appropriate bond-slip laws, to improve the post-peak response of BC joints models [16]. However, this is not an option in ATENA, and recommendations from [17] provide a few suggestions, including: (1) using solid elements; (2) shell elements; or (3) smeared reinforcement. With 8 longitudinal reinforcement from the beam anchored in the joint and 4 column rebar passing through the back of the joint, there is a large amount of bending and shear stiffness that is neglected in these models (see Fig. 4 or Fig. 5 (c)).

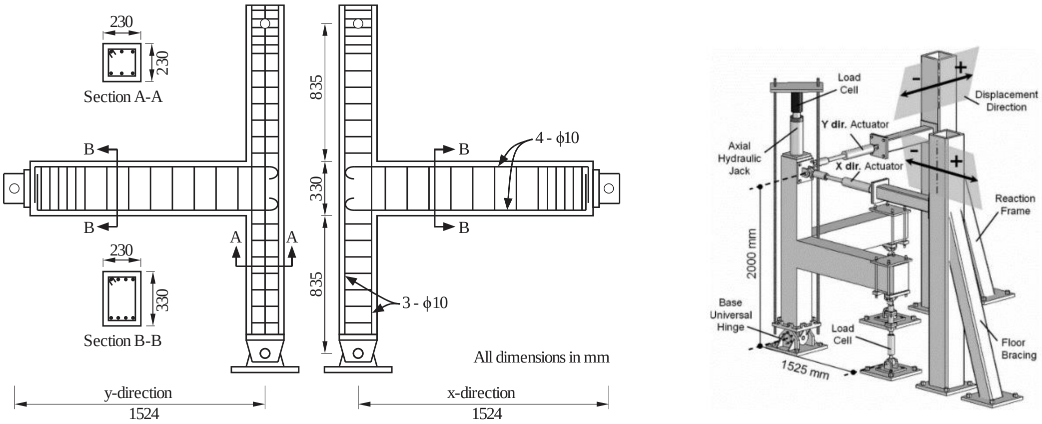


(a) (b) (c)

Fig. 5 – Exterior BC joint: (a) ATENA backbone cyclic response; (b) ATENA cracking pattern; and (c) Experimental damage [13]

3.3. Corner BC Joint

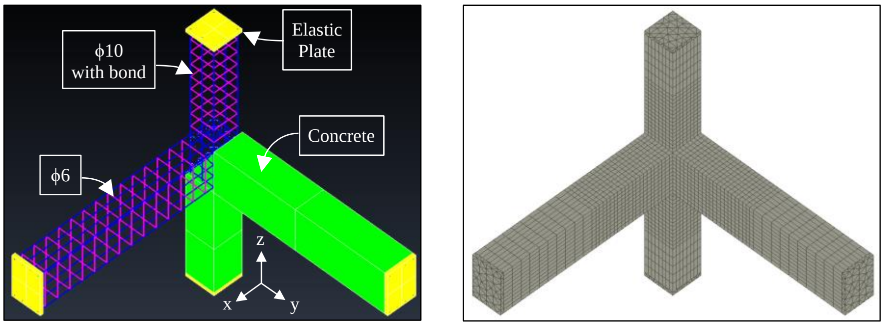
Akguzel and Pampanin (2010) [14] tested 3D corner BC joints with varying axial load using a cloverleaf bidirectional displacement loading protocol. The axial load was updated in real time based on the shear force in the beams, see [14] for details. The 2/3-scaled BC joints were representative of the first-floor joints. The specimen details and experimental setup of the joint are shown in Fig. 6 (a) and (b), respectively. Smooth-bar reinforcement was used, no confining reinforcement was included in the BC joint, and beam longitudinal reinforcement was anchored in the joint with 180-degree hooks.



(a) (b)

Fig. 6 - Corner BC joint: (a) Reinforcement details and (b) Test setup (from [15])

The compressive and tensile strength of the concrete were -17.4 MPa and 2.2 MPa, respectively [14]. The material and mesh of the ATENA model are shown in Fig. 7 (a) and (b), respectively. All translational degrees of freedom were restrained at the centre of the bottom plate under the column. The vertical translation was restricted at the ends of the beams, and lateral translation was prevented at the end of one of the beams for global stability. No torsional restraints were included in the model. The varying axial load was linearly interpolated based on the reported values at a 45-degree skew in each quadrant for each drift level, as discussed in [18].



(a) (b)

Fig. 7 - ATENA model: (a) Material and (b) Mesh

The initial model used only the material properties listed by the authors with the remaining parameters represented as ATENA default. The force-displacement results of the default model are shown in Fig. 8 (top row). The shear failure mechanism in the BC joint was captured by the model; however, the effective stiffness and peak strength were overpredicted. The response of the default model was somewhat expected: these joints were constructed with smooth-bar reinforcement, and an appropriate bond-slip law should be included in the analysis. Experimental evidence has shown that smooth bars result in lower stiffness due to slip, even at early loading stages [19]. The Bagaj model [20] was employed to simulate bond-slip. Bond-slip was only modelled for the straight segments of the bar, and it was first checked against smooth bar bond-slip experiments performed by [21]. Provided the reversed cyclic response of the bond model was selected in ATENA, the results were acceptably close to the experiments. These updates were applied to the corner BC joint model, and the force-displacement results are shown in Fig. 8 (bottom row); -300 mm/km shrinkage strain was also included in the analysis. As shown, the effective stiffness was significantly improved when bond-slip and shrinkage strain were included in the model; it should be noted that the shrinkage strain did not have as significant of an influence on the results as did the bond-slip law. The peak strength in the updated model was slightly higher in the positive x-direction and negative y-direction; however, with the other assumptions in the model (e.g. approximations of axial load), the results are quite good. In both models, degradation was more severe than observed experimentally.

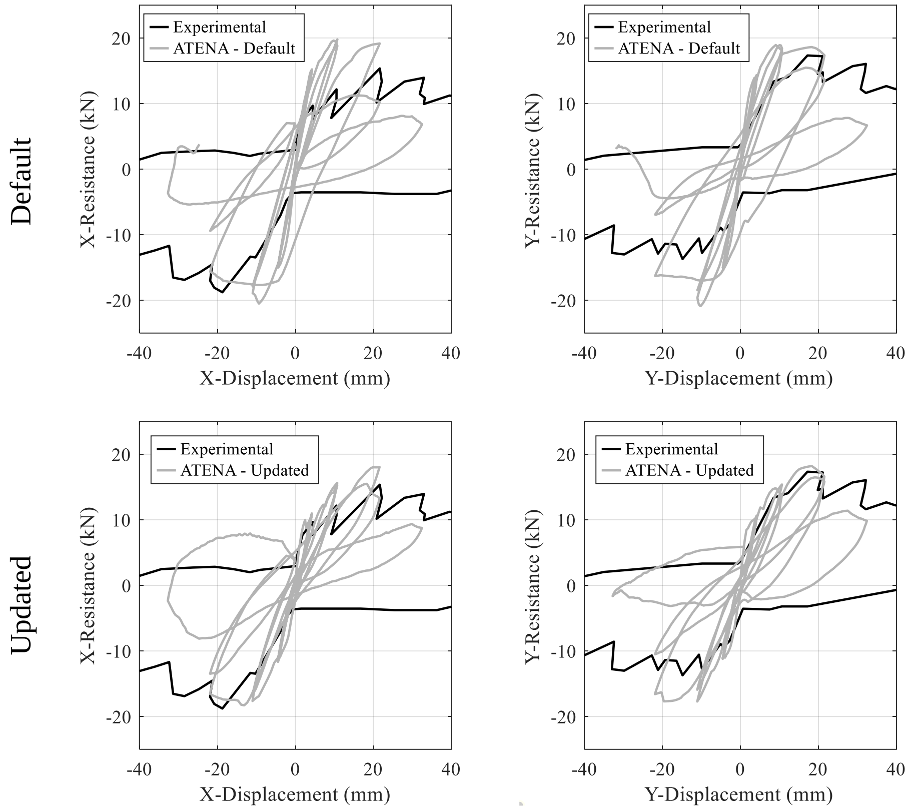
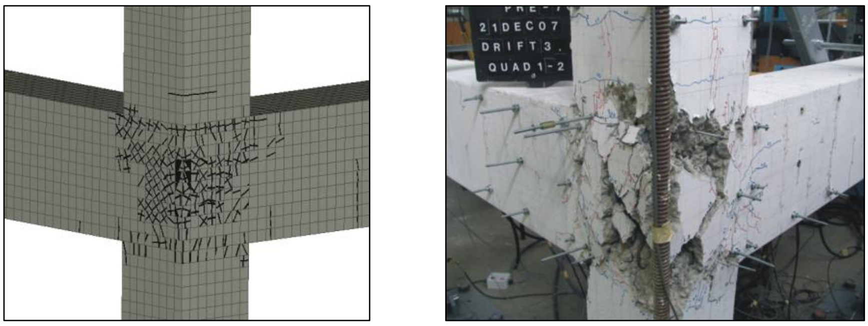


Fig. 8 - Force-displacement response: Default (top) and Updated (bottom)

The cracking pattern of the joint from the updated model of ATENA (cracks ≥ 0.1 mm are shown) are compared to that from the experiments in Fig. 9 (a) and (b), respectively. As shown, the cracking and damage was concentrated in the BC joint.



(a) (b)

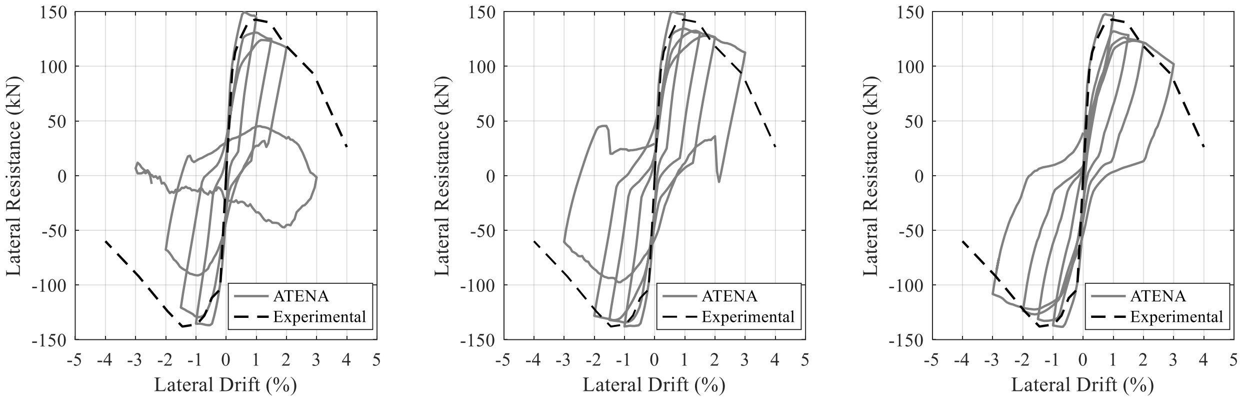
Fig. 9 - Cracking pattern: (a) ATENA and (b) Experimental (from [18])

4. Gapped-Inclined Bracing System Experiments

Two RC planar frames were experimentally tested at the University of Toronto to validate the gapped-inclined bracing (GIB) system, which is a seismic retrofit for ground-level soft-storey buildings; see [9] and [22] for theoretical and experimental work, respectively, completed on the GIB system. The RC frames were representative of the first floor in GLD soft-storey frames. The first test was performed on the conventional frame, and the second test was identical with the GIBs subsequently installed. The lateral displacement of the frames was governed by flexural hinging at the top and bottom of the RC columns; see [22] for details of the experimental results.

The first step in modelling was to calibrate the material properties for the steel and concrete based on coupon and cylinder tests. For the concrete, this was done by modelling a single element with a height equal to the gauge length of the concrete cylinder. The concrete strength of the conventional frame was -32 MPa; the elastic modulus was updated to 38500 MPa; the plastic strain was set to -0.00046; the critical compressive displacement was set to -1.25 mm; and the other parameter were kept as the program defaults.

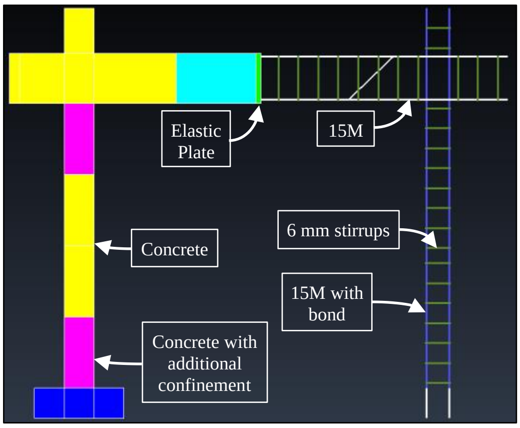
The lateral displacement of the RC frame was governed by plastic hinging at the top and bottom of the RC columns. As a result, a cantilever column, assuming the inflection point at mid height, was used to check the response when modelling different mechanisms (e.g. bond-slip). One cycle at each drift amplitude (1%, 1.5%, 2%, 3%, and 4%) was attempted. The default model is shown in Fig. 10 (a). As shown, the initial stiffness and peak strength were well captured. However, the post-peak degradation was more severe in the model. With yielding and crushing in the plastic hinge, the longitudinal reinforcement, represented as truss elements, became unstable with increasing degradation of its surrounding concrete; this led to "buckling" of the reinforcement. The default model may represent a conservative approach to modelling GLD frames or columns and may fine for practical applications. However, some attempts to improve the response are subsequently described. The shear and bending stiffness of the rebar was simulated using smeared transverse reinforcement over the plastic hinge zone, as suggested in [17]; the smeared reinforcement was based on the volumetric ratio of the longitudinal reinforcement to the concrete. The additional confinement in the plastic hinge zone increased the ductility capacity of the model, as shown in Fig. 10 (b). Finally, strength degradation and the unloading stiffness were more accurately represented when bond-slip was included (Fig. 10 (c)). Bond-slip of deformed reinforcement may stem from crushing of the concrete adjacent to the lugs of the reinforcement, or from splitting cracks, which were observed experimentally.

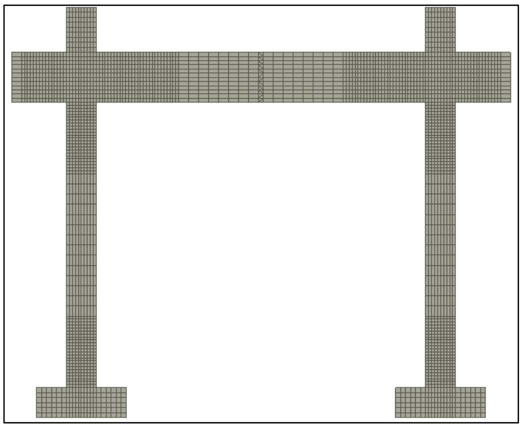


(a) (b) (c)

Fig. 10 - ATENA result: (a) Default; (b) Additional confinement; and (c) Confinement + bond-slip

The calibrated ATENA model and mesh of the conventional frame are shown in Fig. 11 (a) and (b), respectively. Bond slip was excluded from the beam rebar and the rebar anchored into the foundation. A fixed boundary condition was applied to the bottom of the foundation, and the lateral displacement was applied the elastic plate at the centre of the beam.

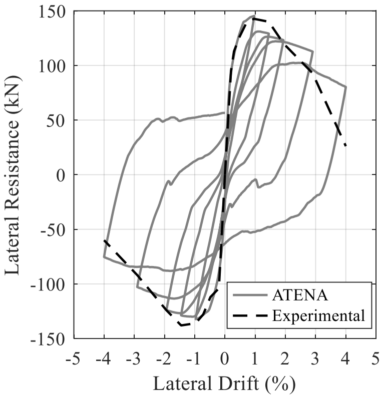


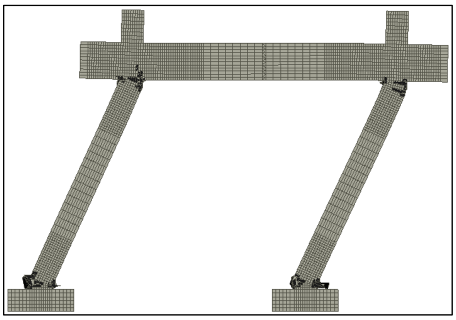


(a) (b)

Fig. 11 - ATENA model: (a) Materials and (b) Mesh

The force-deformation response of the calibrated model is shown in Fig. 12 (a). The stiffness, peak strength, and post-peak degradation were fairly well captured by the model. The flexural hinging at the top and bottom of the RC columns was well captured in ATENA, as illustrated by a comparison between the cracking pattern from ATENA (Fig. 12 (b)) and the damaged specimen after the experiments (Fig. 12 (c)).





(a) (b) (c)

Fig. 12 – Conventional frame results: (a) ATENA force-displacement; (b) ATENA cracking pattern; (c) Conventional frame damage

The retrofitted frame was modelled by updating the concrete material properties to match that of the experimental specimen. A sketch of the GIB-to-frame connection used in the experiments is shown in Fig. 13 (a), and the installation of the GIB on the retrofitted frame is shown in Fig. 13 (b). The method used to model the GIB-to-frame connection is shown in Fig. 13 (c). The GIBs were modelled as truss elements. These trusses were connected to steel plates at the top and bottom of the frame. The top steel plate was fixed to the bottom side of the beam in only the vertical direction (to transfer tensile and compressive forces), with the other degrees of freedom released; care was taken to ensure that shear connection was not modelled between the steel plate and the concrete, which would unrealistically increase confinement in the beam around the connection. The bottom connection was made using two steel plates separated by a small gap, equal to the gap of the brace. A nonlinear spring with high compressive stiffness and essentially no tension stiffness was used on the bottom side of the bottom plate to represent the compression-only nature of the brace. To ensure that the gap element response was adequately captured, the “Use current coordinates” option was selected in the “Fixed Contact for Surface” boundary conditions between the two elastic plates.

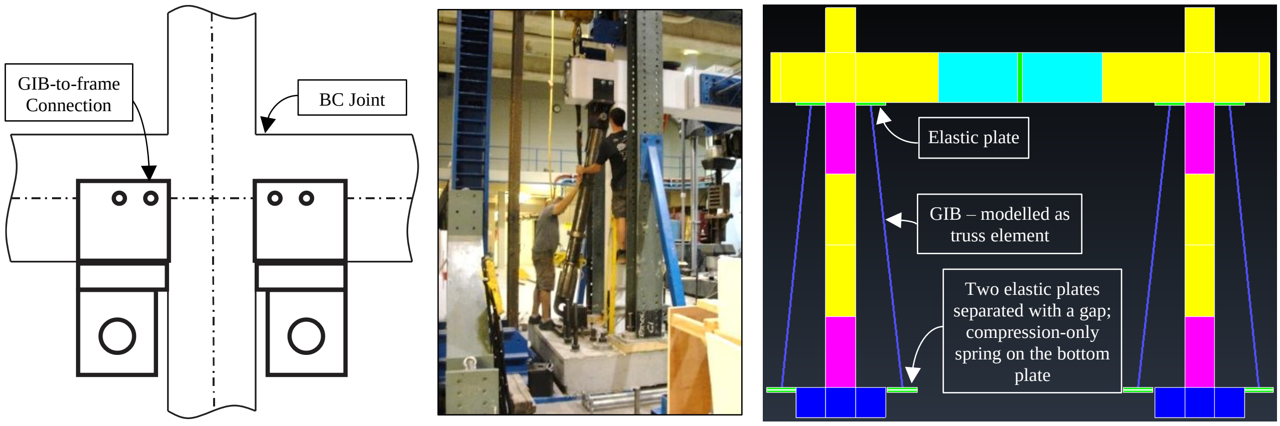


Fig. 13 - ATENA model of the GIB connection: (a) Top connection [adapted from [20]; (b) GIB installation [20]; and (c) ATENA model

Again, one cycle was completed at each drift amplitude up to 7% (1%, 1.5%, 2%, 3%, 4%, 5%, 6%, and 7%). The numerical results to 4% drift (Fig. 14 (top)) are compared to the experimental results (Fig. 14 (bottom)). The response was well captured up to 4% drift. The lateral force-displacement response has been separated into the contributions from the GIBs (black) and columns (dark grey), which is shown in the most left column of the figure. The centre column of the figure illustrates the distribution of vertical forces between the GIBs and existing columns. As shown, the ATENA model captures well the transfer and axial load from the columns to the GIBs to increase the displacement capacity of the columns. The right column in the figure shows the cracking and damage pattern at 4% drift. Cracking was largely concentrated at the top and bottom of the columns.

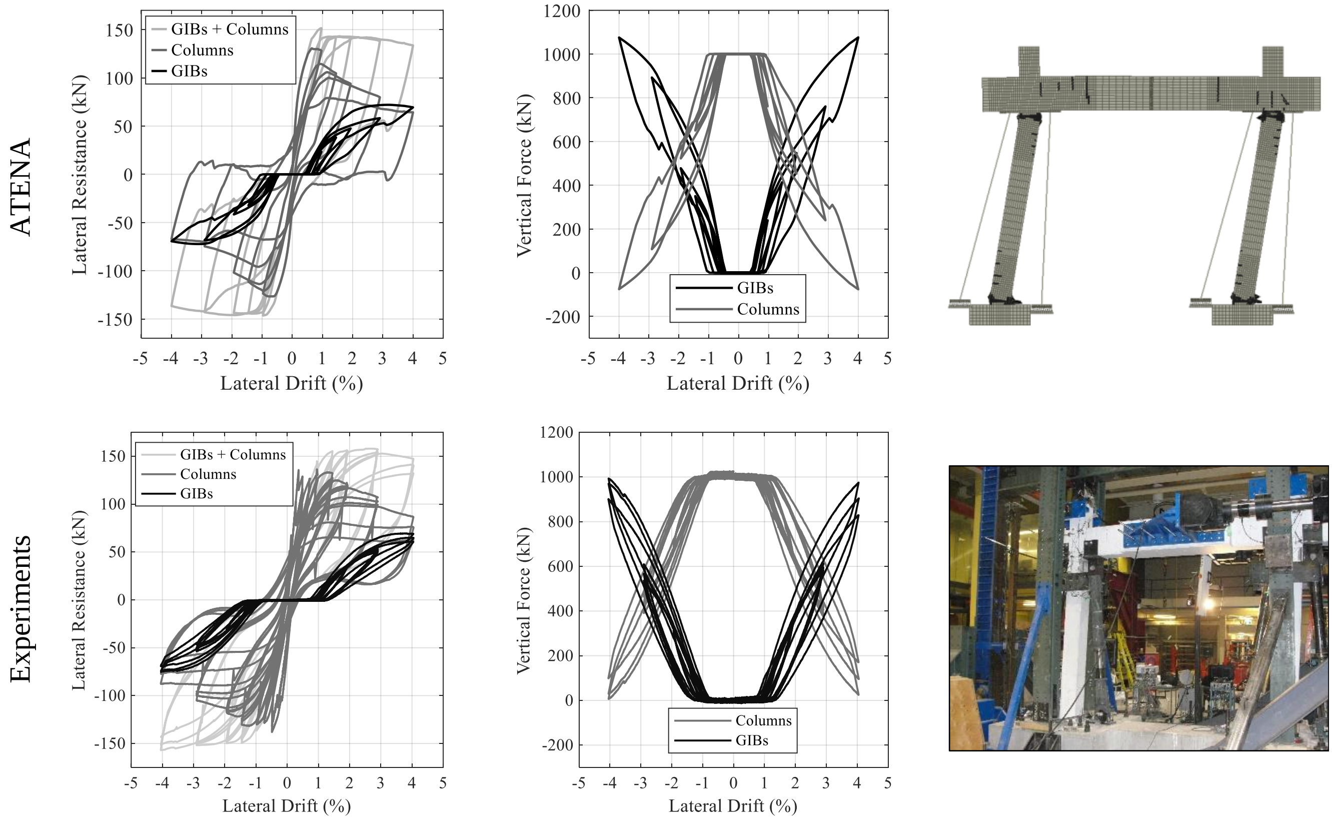


Fig. 14 - Retrofitted Frame Results: (a) Force-displacement ATENA; (b) Force-displacement Experiments; (c) GIB vertical reaction ATENA; and (d) GIB vertical reaction Experimental

5. Conclusions

Gravity-load-designed (GLD) structures exists in many seismic-prone regions throughout the world, and these structures have a history of poor seismic performance. To develop effective seismic retrofitting strategies for poorly detailed GLD structures and components, an accurate assessment of their capacities is required. This paper described a modelling procedure for GLD RC components. Five experimental specimens were modelled using ATENA, a nonlinear finite element analysis program for plain and reinforced concrete components. Modelling results were presented as a progression, starting with the default material properties; more sophisticated models were then presented to include additional phenomena, such as concrete shrinkage and rebar bond-slip.

It was found that the beam-column joints modelled herein, constructed with deformed reinforcement, had an improved response, with respect to effective stiffness and peak strength, when shrinkage strain was included before the imposed displacements. For the beam-column joint constructed with smooth bar reinforcement, the results were significantly improved when rebar bond-slip law should be included, where the bond-slip law accounts for cyclic degradation.

The soft-storey RC frames from the experimental campaign of the gapped-inclined bracing (GIB) system was modelled. It was found that ATENA was able to capture the response of the conventional and retrofitted specimens after additional confinement was included in the plastic hinge locations of the RC columns and bond-slip was modelled for the rebar. The additional confinement was meant to incorporate the bending and shear stiffness of the longitudinal rebar in the column. The strength, stiffness, and post-peak degradation of the conventional frame was fairly well represented in ATENA. The compression-only response of the GIB was well-simulated and the force-displacement response of the retrofitted frame was well captured up to 4% drift. The transfer of axial load between the existing columns and GIBs was also well simulated using ATENA.

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6. References

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