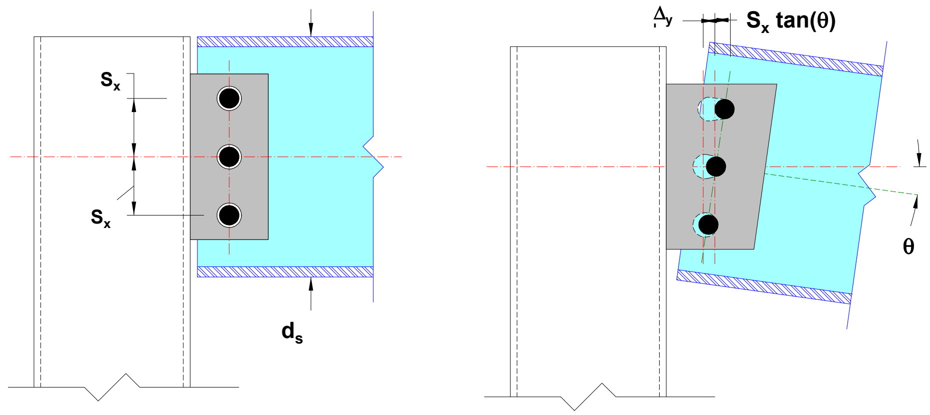
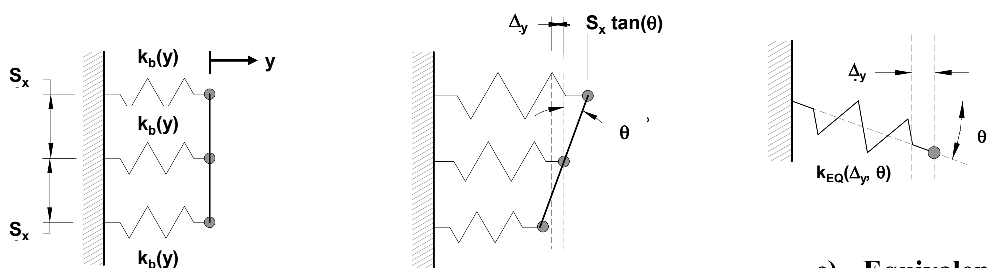


a) Connection Configuration

b) Deformation on Bolt Holes

Figure 5 - Beam with Shear-Tab SC with (03) rows of bolts

The force–deformation function is developed using two degrees of freedom (i.e., lateral deformation and rotation), as shown in Figure 6. The models developed by Oosterhof and Driver (2016) predict accurately the connection response for corresponding tests simulating progressive collapse. The connection strength/ beam yielding strength ratio for specimens with shear tab connections varies 5% - 10%.



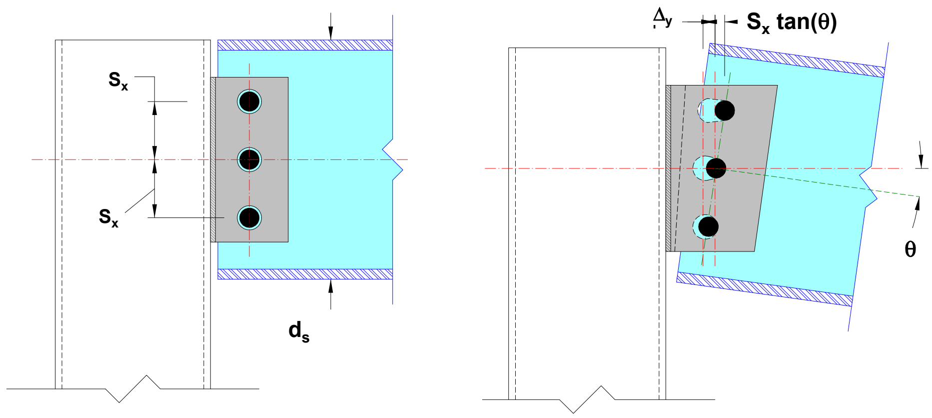
a) For Displacement

b) For Rotation & Displacement

c) Equivalent Spring

Figure 6 - Shear-Tab SC Model

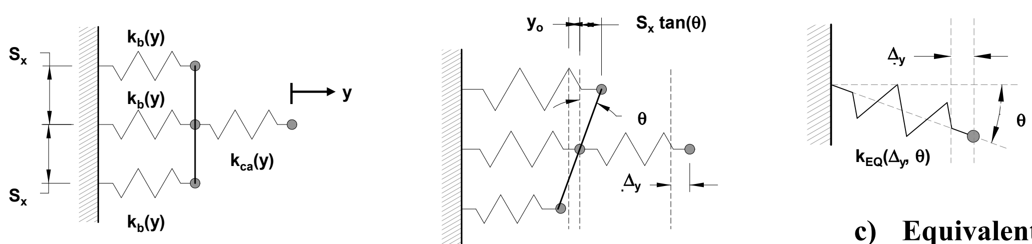
Double Angle bolted-bolted connection – Bending: Figure 7 a) and Figure 7 b) depict the condition of the connection and the effect of support rotation in the components of the connection, respectively. As with the shear tab in bending, the centroid of the connection is subjected only to lateral translation, while the rest of the bolts are subjected to an additional translation due to the eccentricity. In addition to the parameters included in the double angle connection in tension, the eccentric deformation is taken into account in the force-deformation function.



a) **Connection Configuration** b) **Deformation on Bolt Holes**

Figure 7 - Beam with Double Angle Bolted-bolted SC with (03) rows of bolts

The force deformation function is developed using two degrees of freedom (i.e., lateral deformation and rotation) as shown in Figure 8. The models developed by Oosterhof and Driver (2016) were able to predict accurately the connection response for corresponding tests simulating progressive collapse. The connection strength to beam yielding strength ratio for specimens with double angle bolted-bolted connections varies 4% - 7%.

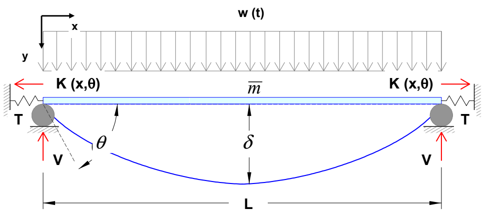


a) **For Displacement** b) **For Rotation & Displacement** c) **Equivalent Spring**

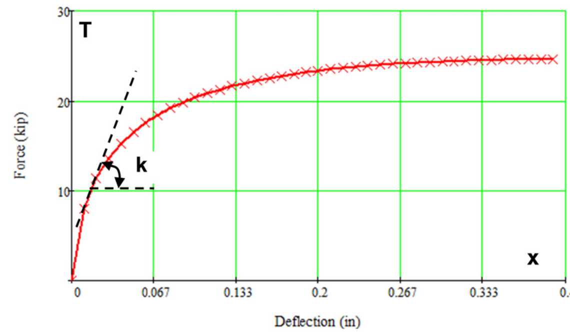
Figure 8 - Double Angle Bolted-bolted SC Model

MODELS FOR BEAMS SUBJECTED TO BLAST LOADING

The models discussed in the section above, for the shear tab and double angle bolted-bolted connections subjected to tension and bending, are incorporated into a MDOF model to predict the response of a beam subjected to blast loading. Figure 9 depicts a generic 3DOF proposed model. Some simplifications are included such as a) moment at the support is neglected, b) connection strength in the connection force-deformation function is assumed to be reached at the failure of the extreme bolt row (or bearing) only.



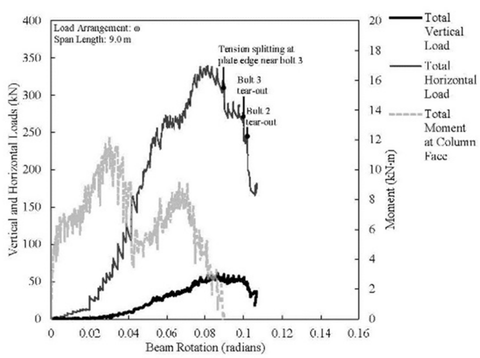
a) Beam Model Including Connection Flexibility



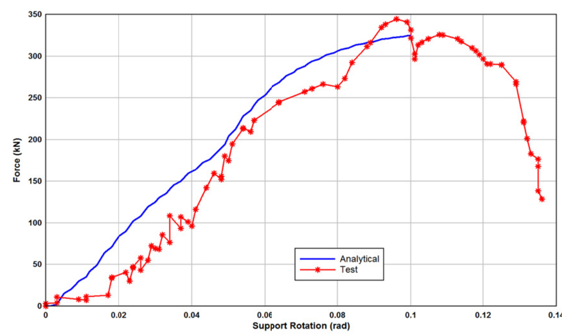
b) Axial Force-Deformation Relation for a Connection Type

Figure 9 - 3DOF model per generic connection type

The approach described above is validated using the series of tests carried out by Oosterhof and Driver (2015) using the corresponding rotation relationship from the tests simulating progressive collapse. Figure 10 and Figure 11 show the comparison of the proposed model against the corresponding test for a selected shear tab and double angle bolted-bolted connections, respectively.

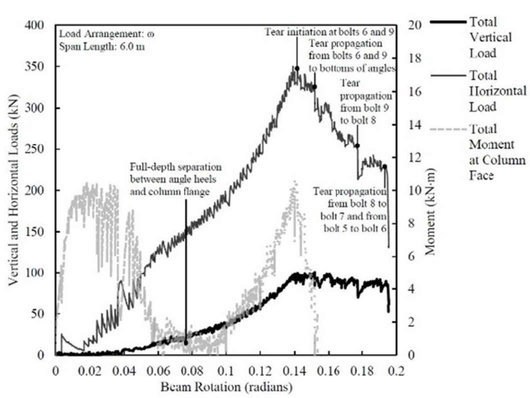


a) ST3B-2 Test Plot

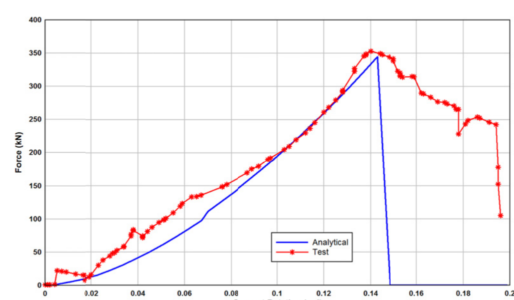


b) Model – Test Comparison

Figure 10 - Shear Tab SC Validation



a) DA3B-2 Test Plot



b) Model – Test Comparison

Figure 11 - Double Angle Bolted-Bolted SC Validation

Based on the approach described in this section, the resistance function for blast analysis can be developed using either of the methodologies proposed as follows:

Simplified 2DOF: Resistance based on an equivalent elasto-plastic spring (as shown in Figure 9 b)). The properties of the equivalent spring can be obtained using the equal strain energy principle. After assuming a shape function for the beam deflection the corresponding support rotation can be used to condense the 3DOF model into a 2DOF model.

Refined MDOF: Resistance based the actual non-linear spring rotation-deformation relationship as shown in Figure 10 and Figure 11. Relationships between moment, rotation and resistance can be developed considering strain distribution for combined flexure and axial tension (see Figure 13). The support rotation can be obtained for the connection force-rotation relationship. Also, the strain function can be implemented to compute the strain rate during the dynamic analysis to compute the Dynamic Increase Factor (DIF) using, for example, the Cowper-Symonds formulation.

As an example for the 2DOF approach described above, the force-deformation function for the shear tab SC used in the Test ST3B-2 shown in Figure 10 is obtained after condensing the rotation and axial DOFs using the test set-up configuration. Thus, the support deformation is the one corresponding to the centroid of the connection. The corresponding force-deformation is shown in Figure 12

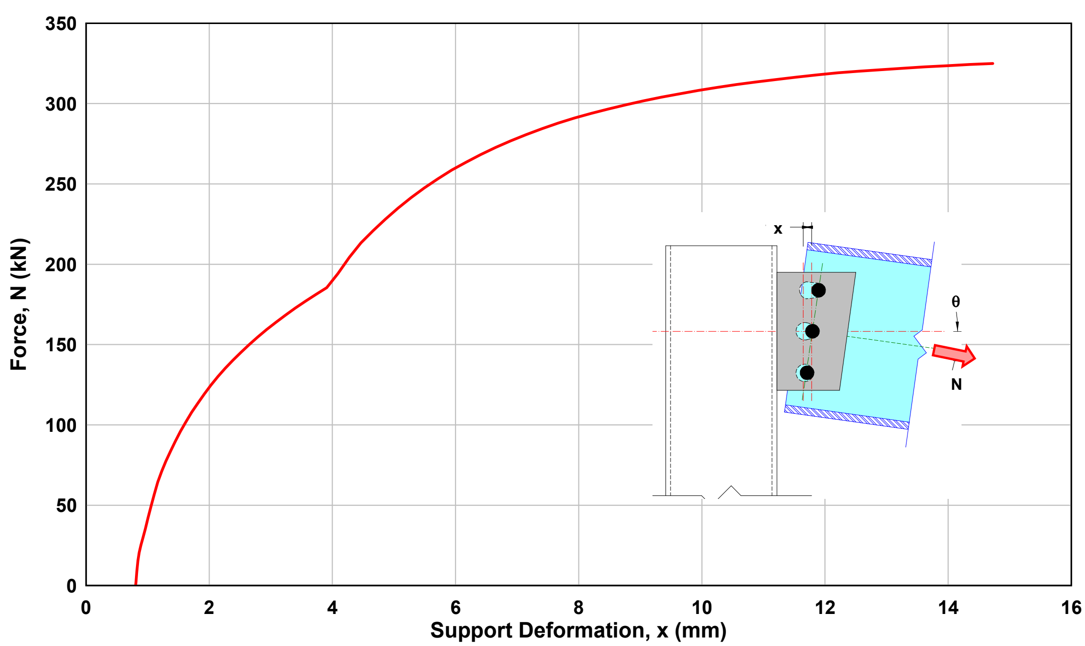


Figure 12 - Shear Tab SC Force Deformation (Test ST3B-2)

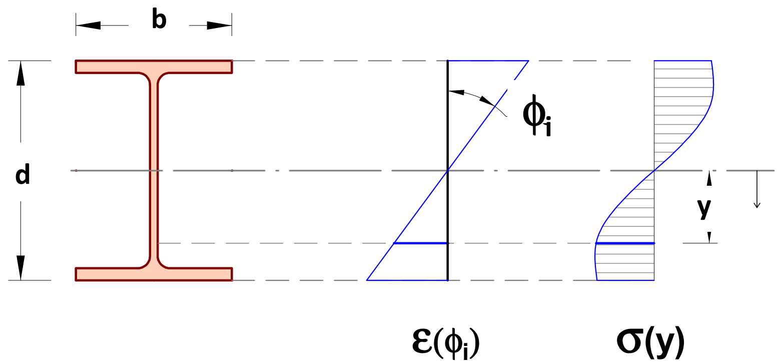


Figure 13 - Strain and Stress of Beam in Flexure Using the Fiber Method

$$M(\phi_i) = \int_0^d b_y \; y \, \sigma(y) \, dy$$

Equation 1 –Moment at any given section along beam

Currently, the Refined MDOF methodology is under development and only the Simplified 2DOF is addressed in this paper. As an example, Figure 14 depicts the resistance function for the WF-beam used above with double angle bolted-bolted connections.

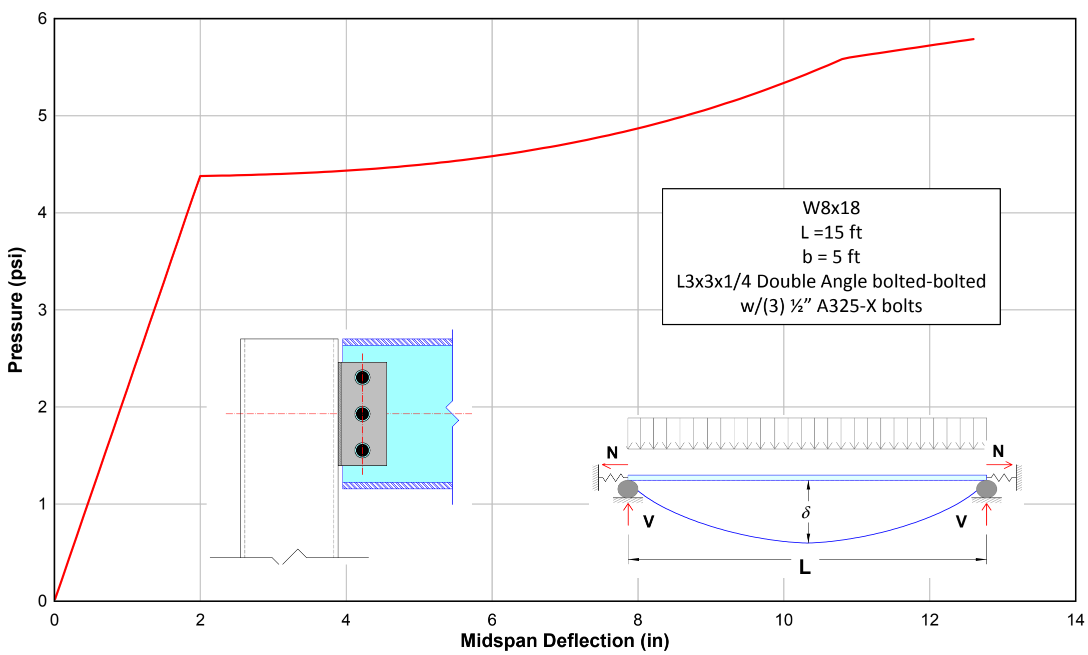


Figure 14 – Resistance Function for WF-beam w/Double Angle Bolted-Bolted SC

Also, the tensile and shear reactions quasi-static functions for the same WF-beam used above are shown in Figure 15.

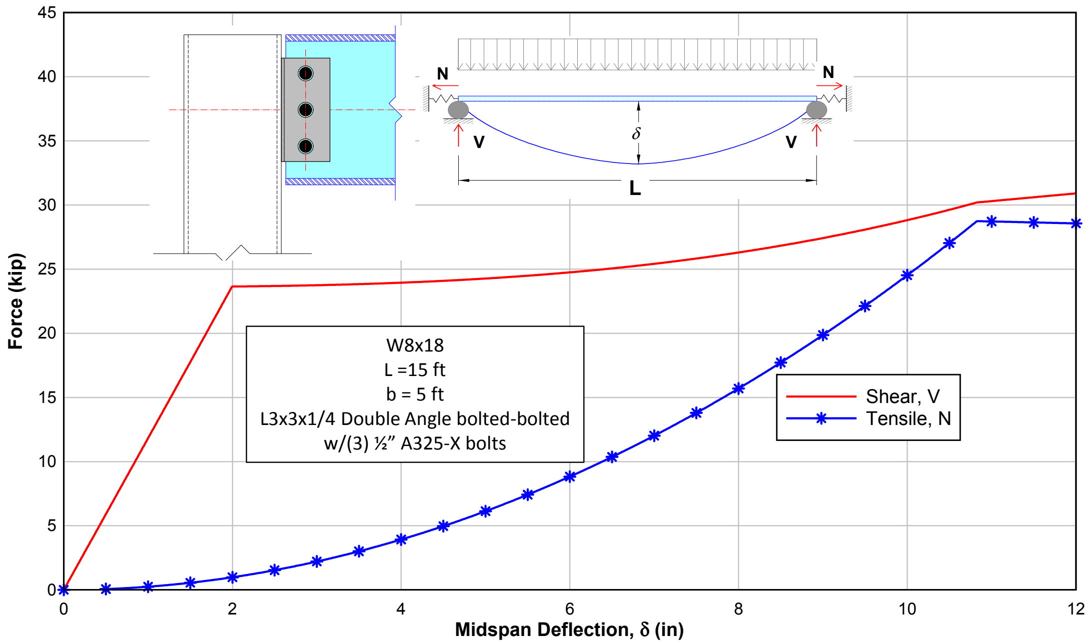


Figure 15 – Example of Reaction Forces in W-beam w/Double Angle Bolted-Bolted SC

The resultant reaction quasi-static function is developed and depicted in Figure 16 using two different sets of angles in the connections. This figure shows that when the effect of strength and stiffness of the connection is included, the resultant force reaction on bolts is 75% greater than the reaction force computed based on flexure only with a non-yielding support.

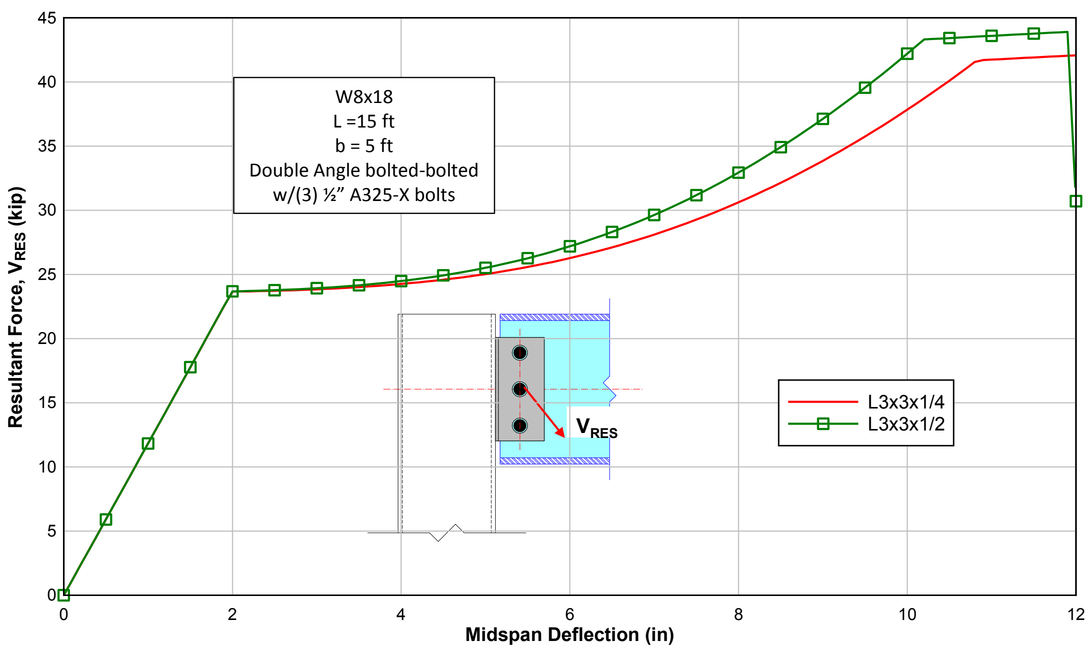


Figure 16 – Example of Resultant Shear on Bolts of Double Angle Bolted-Bolted SC

CONCLUSIONS

Based on the previous sections, the following conclusions can be drawn:

- Models developed for progressive collapse prediction can be used for blast analysis.
- Results of quasi-static tests simulating progressive collapse for simple connections show that support rotation of beam does not increase significantly the moment at the support. Rather support rotation changes the transversal deformation across bolt location.
- Prediction of connection performance using pure tensile loads can be made incorporating the rotational effect in the connection as described above.
- Beams connections subjected to blast loading or progressive collapse should be designed so that ultimate capacity is controlled by ductile failure modes.
- Welds should be avoided in connections near critical zones (i.e., plastic hinges) to avoid any increase of stiffness, reduction of ductility, or reduction of strength (residual stresses after heat).
- From the progressive collapse tests, the connection strength to beam yielding strength ratio reached 10% and 7% for shear tab and double angle bolted-bolted connections, respectively. All of those connections were controlled by ductile failure modes.
- In case the development of tensile force in the connection is not desired, a properly detailed connection should be considered providing slotted holes as shown in Figure 17

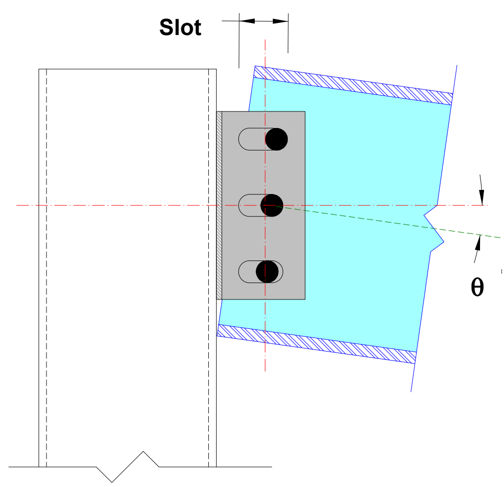


Figure 17 - Connection Detailing to Avoid or Dealing with Tensile Membrane Loading

LIMITATIONS AND FUTURE WORK

Although this paper addresses only shear tab and double angle bolted-bolted connections, similar approaches could be used for tee shear (T-stub) and shear end-plate connections. A properly detailed connection would provide flexibility and be controlled by ductile failure modes.
The Refined MDOF formulation described above could incorporate the tee shear and shear end-plate connections. The MDOF formulation will include the strain rate effect in beam and connection components only for the controlling failure mode.

REFERENCES

AISC, "Design of Blast Resistant Structures" American Institute of Steel Construction, 26 Steel Design Guide (2013)

Blewitt, J. "Experimental and Analytical Force-Deformation Curves for Bolted Connections". The Department of Civil Engineering and Engineering Mechanics. The University of Arizona; Tucson, AZ (1984)

Holgado, D. and Barker, D. "Effect of Reaction Forces on Steel Members Subjected to Blast Loading" Engineering Mechanics Institute Conference; Evanston, IL (2013)

Holgado, D. et al. "Detailing of Steel Structures Subjected to Blast Loading". 86th Shock & Vibration Symposium; Orlando, FL (2015)

Oosterhof, S.A., and Driver, R.G. "Behavior of Steel Shear Connections Under Column-removal Demands." Journal of Structural Engineering, American Society of Civil Engineers, vol. 141, no.4 (2015)

Oosterhof, S.A., and Driver, R.G. "Shear Connection Modelling for Column Removal Analysis." Journal of Constructional Steel Research, vol. 117, pp. 227-242 (2016)

Rex, C. "Behavior and Modeling of A Single Plate Bearing on a Single Bolt" Research Report No. CE/VPI-ST 96/14. Virginia Polytechnic Institute and State University, Blacksburg, VA (1996)

Stoddart, E. "Development of Component-Based Connection Modelling for Steel Framed Structures Subjected to Blast or Progressive Collapse". PhD. Thesis. University of Southampton. United Kingdom (2012)

UFC 3-340-02. "Structures to Resist the Effects of Accidental Explosions" (former TM 5-1300), Department of Defense (DoD), Unified Facilities Criteria; 2014

Is the Load Transfer Mechanism of Each Story in a Multi-Story Building the Same Subjected to Progressive Collapse?

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Abstract

Progressive collapse is global structure performance, which involves all the stories above a removed column. However, previous experimental research work is more concentrated on single-story sub-structures or assemblies, mainly due to the concerns of cost and safety issues. In engineering practice, how to translate the research results of single-story sub-structures into multi-story structures becomes more interesting and urgent for engineers to design or rehabilitate structures against progressive collapse. In this paper, a planar and a three-dimensional reinforced concrete (RC) frames are modeled with fiber-based plastic hinges for nonlinear static analysis. The numerical models are initially validated by the experimental results of RC framed sub-structures, and then are used to investigate whether the load transfer mechanism of each story in a multi-story building subjected to progressive collapse is the same, and identical to the one obtained from a single-story substructure test. The parameters to be studied include loading positions, boundary conditions, the number of spans, explicit modeling of slabs.

Keywords: Load transfer mechanism; Multi-story building; Reinforced concrete; Progressive collapse.

INTRODUCTION

Since the collapse of Ronan Point building in the UK in 1968, in particular the collapse of the World Trade Center in 2001, the progressive collapse of buildings have attracted a lot of research interests over the world. The researchers have conducted a great many experimental and numerical investigations on the load transfer mechanisms of the structures under progressive collapse. Yi et al.(2008) tested a one-third scaled 4-span-3-story reinforced concrete (RC) planar frame under a middle column removal scenario, and qualitatively showed that the load transfer mechanisms of the RC beams in the first story above the ground include compressive arch action and catenary action. Sasani et al. (2011) explosively removed four adjacent first-story columns of an actual 11-story building to investigate the responses of the building and numerically identified two primary gravity load transfer paths, including the flexural-axial response of the second-floor deep beams, and the Vierendeel action of the flat plate structural system in floors above. Xiao et al (2015) experimentally investigated the dynamic responses of a half-scaled three-story RC frame building under different column removal scenarios, and the shift from moment-resisting mechanism to catenary mechanism was identified after the removal of the two first-story exterior columns.

As multi-story frames are typically large and expensive, only very limited experiments were conducted. In comparison, single-story specimens are much more feasible and more focused on the quantitative effects of relevant parameters. For instance, single-story RC beam-column assemblies (Qian and Li, 2013, Yu and Tan, 2013a, b) and beam-slab assemblies(Qian and Li, 2012, Pham and Tan, 2013, Dat and Tan, 2015, Lu, et al., 2016) were investigated for the effects of the specimen geometric parameters and reinforcement ratios et al. on the load transfer mechanisms under different column removal scenarios. Moreover, some analytical approaches have been proposed to calculate the progressive collapse resistance of single-story assemblies(Yu and Tan, 2014, Kang and Tan, 2016).

Compared with single-story assemblies, actual structures have more restraints and accordingly have more load transfer paths. Therefore, it is imperative to investigate whether the load transfer mechanism of each story is the same and whether the progressive collapse resistance of each single story can be directly summed up to derive the total resistance of multi-story structures. In this paper, systematical numerical analyses are conducted to answer the above two questions. Moreover, the parameters to be studied include loading positions, boundary conditions, the number of spans, explicit modeling of slabs.

VALIDATION OF THE NUMERICAL MODEL

In this paper, multi-story planar and three-dimensional RC frames are modeled with SAP2000. The nonlinear static (or pushdown in vertical direction) analyses are conducted to obtain the structural resistance of overall structures and beams of each story above a removed column, as well as the internal forces (such as axial force and bending moment) of the beams. The development of beam internal forces can help to identify the load transfer mechanisms.

The validation of the numerical model is conducted based on the test of Yi et al.(2008), in which a 1/3 scaled RC planar frame with four spans and three stories was designed and fabricated in accordance with Chinese code (2002), as shown in Fig. 1(a). The column to be removed was replaced by two hydraulic jacks with a load cell. At the top of the middle column, a constant force of 109kN was applied by a hydraulic actuator to simulate axial force in the column. During the test, the hydraulic jacks unloaded to represent the effect of column removal. The cross-sectional dimensions and the reinforcement of the beams and columns are shown in Fig. 1(b).