Enclos contributed materials and curtainwall units for the blast testing of Momentive's two-part structural elastomeric adhesive/sealant product "UltraGlaze SSG4600".

Blast Performance of Structural Glazing

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Typical analysis procedures for blast resistant glazed framing members fall into two categories, finite element multiple degree of freedom analysis and single degree of freedom (SDOF) analysis. Finite element analysis is not always economically feasible, and simple SDOF analysis results in unnecessarily conservative sections that may not be able to meet the architect's design intent. Conservatively sized sections have the additional detriment of increasing the load to structure, due to the "glass fails first" methodology required on a vast majority of projects. Significant gains/savings can be achieved by sequentially performing a SDOF analysis of each system element, starting with the glazing. Each successive element is then loaded with the response of the previous element, until the load is resolved into the structure.

INTRODUCTION

Events of the past decade have made blast resistant structures and blast resistant curtainwall a serious consideration for projects that in the past would have balked at the cost or aesthetic impact resulting from hardening the structure. Typical curtainwall analysis usually consists of segmenting the system into floor to floor spans and performing a single degree of freedom analysis. SDOF analysis can be done quickly, but is quite conservative. Conservative analysis in turn results in a large and costly cross section, and due to the glass fails first methodology, increases the load to structure. The other end of the spectrum is hydrocode analysis and finite element analysis. These analysis techniques can be quite precise, but are costly due to the time required to construct and analyze the models. In additional to being time intensive, specialized modeling software and modeling expertise are needed to get precise results. Sequential single degree of freedom (SSDOF) analysis offers a compromise. SSDOF analysis utilizes a series of SDOF analysis to predict the response of the system as a whole. SSDOF analysis provides less conservative analysis for a modest increase in time, allowing the structure to be hardened more economically and provide more options architecturally. Below we will discuss SSDOF methodology, its advantages, limitations, and comparison with SDOF analysis results.

SEQUENTIAL SINGLE DEGREE OF FREEDOM (SSDOF) ANALYSIS METHODOLOGY

SSDOF analysis decouples each component of the curtainwall system and analyses each component separately, but recognizes each component is a part of larger system. Each component is loaded by the response of the component immediately preceding it on the load path. The series of decoupled analyses for curtainwall begins with the prescribed overpressure and impulse being applied to the glazing. Specifications typically require specific government developed glass analysis software program to be used to analyze the glazing. These programs produce a glazing perimeter load functions that then may be used to load a beam model of the curtainwall system. The response function of the curtainwall system is then used as the load function to the curtainwall anchor. Finally, the curtainwall anchor response is used as a load function for resolving the loads to the building structure.

SEQUENTIAL SINGLE DEGREE OF FREEDOM (SSDOF) ADVANTAGES

The first and largest benefit to using SSDOF analysis is the use of existing experimentally validated glazing analysis software. Significant performance gains can be realized by taking advantage of the glazing's ability to dissipate energy due to glass breaking and how the glazing response changes the shape of the load function to the curtainwall framing system.

In addition to reducing the amount of energy impinging the curtainwall framing, the load function shape differs from the typical idealized linearly decaying load function that impinges the glazing. The glazing response loads the curtainwall with a lower peak and longer duration, resulting in a less impulsive

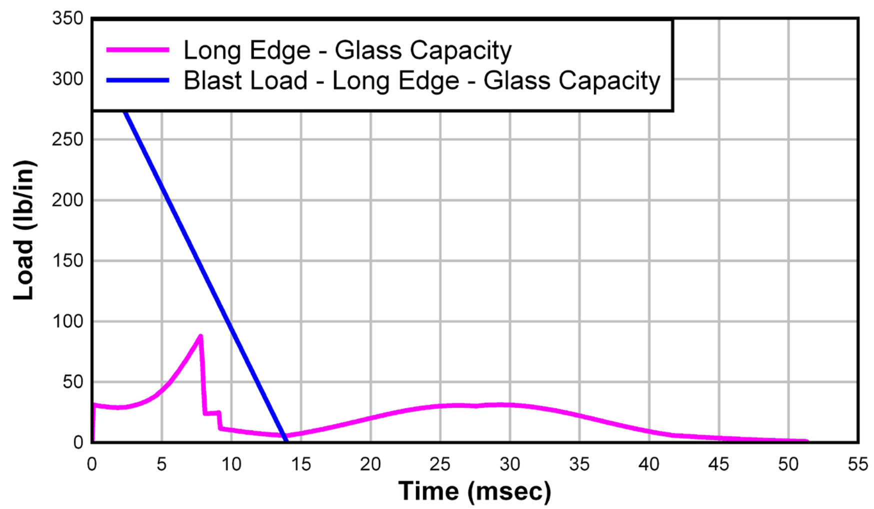
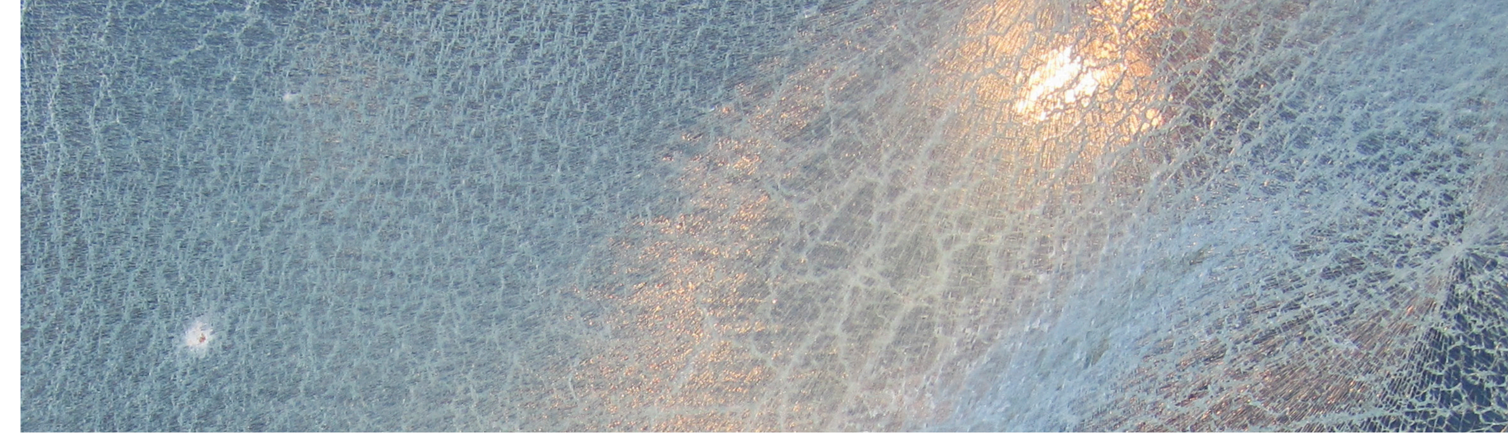


Figure 1: Pressure Tributary Load Function and Glazing Response Load Function

Figure 1 illustrates the differences between a pressure and tributary loading and the loading results of glazing analysis software. Linear decaying pressure and tributary loading (blue line) has a higher magnitude and much shorter duration. This results in a highly impulsive load. Glazing analysis software results (magenta line) incorporate glass breakage and flexibility of the glazing. The glazing response load function illustrates the breakage of the outer and inner lite of an insulated glass unit with only the membrane providing final load resistance. The peaks of the load function are followed immediately by sharp drop offs, which represent the glass breaking. Load applied to the curtainwall frame after the inner lite has fractured is provided by the inboard lite's interlayer. Conservation of mass and energy principles dictate that the drop offs represent energy and momentum being dissipated, therefore requiring the curtainwall system to store or dissipate less energy.



load (see figure 2). Due to curtainwall's low mass, reducing the impulse and increasing the load duration allows the curtainwall system to mobilize the mass and stiffness to resist the load.

Limited gains can be found in using SSDOF over SDOF for the curtainwall framing system. SDOF already includes the strain energy dissipated due to the formation of plastic hinges. A source of performance gains for the curtainwall framing system is using a high strain rate stress strain curve in lieu of using load and mass approximation [1]. A high strain rate stress strain curve is used to allow elements to behave according to the strain induced rather than assuming an elastic or plastic behavior. A series of model comparisons using load mass factors and stress strain curves were ran. Models using a stress strain curve returned a 4.7% decrease in maximum deflections.

Curtainwall anchors are much stiffer than other curtainwall components and frequently required to behave elastically when subjected to the full capacity of the framing system. With these restrictions, anchors contribute minimal gains and may be assumed to be a rigid member transferring load directly to the structure without alteration. SSDOF analysis returns similar results as a SDOF analysis.

SEQUENTIAL SINGLE DEGREE OF FREEDOM (SSDOF) LIMITATIONS

SSDOF analysis loses fidelity due to the decoupled nature of the analysis. Each decoupling replaces the flexibility of the sup-

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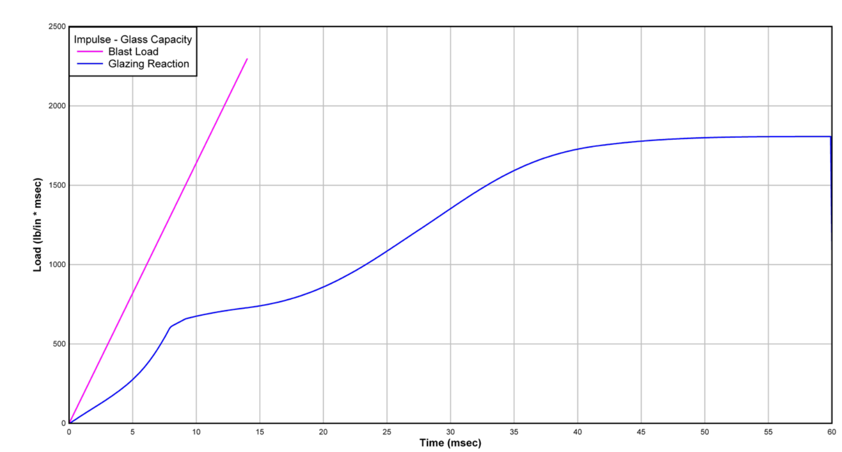
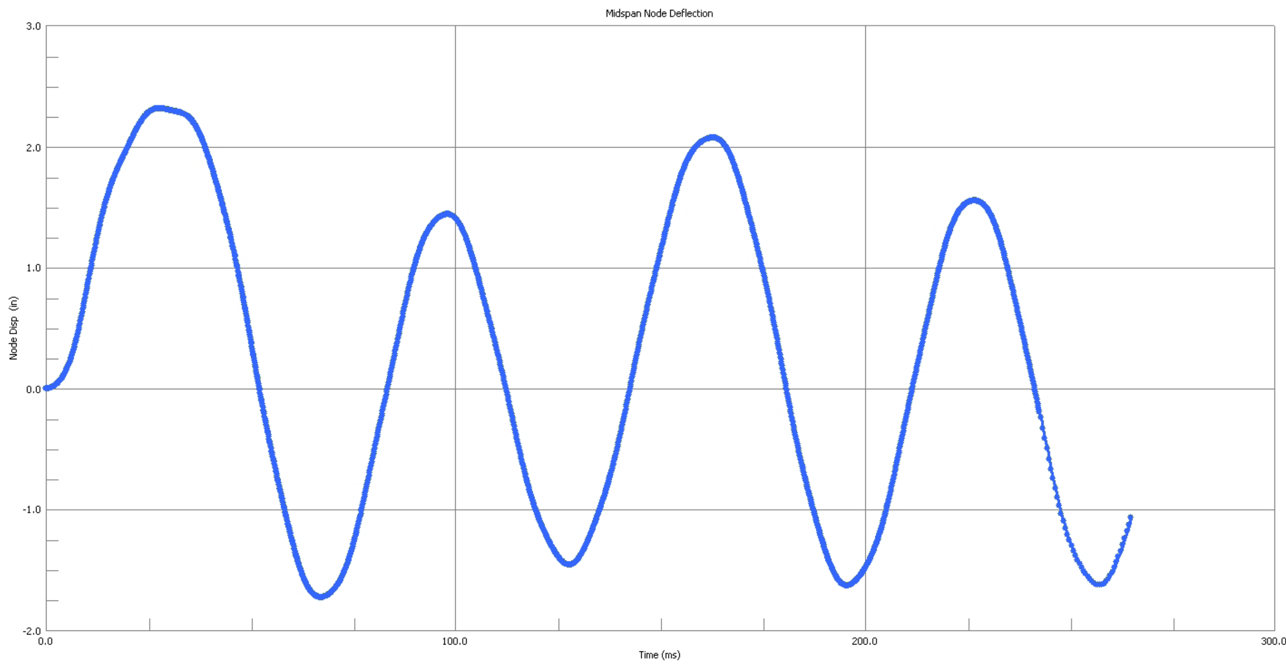


Figure 2: Impulse Comparison - Glazing Response Capacity (blue) and Blast Pressure (magenta)



SINGLE DEGREE OF FREEDOM MULLION RESPONSE		
Ductility	Support Rotation (degrees)	Maximum Displacement (in)
2.669	5.29	5.56

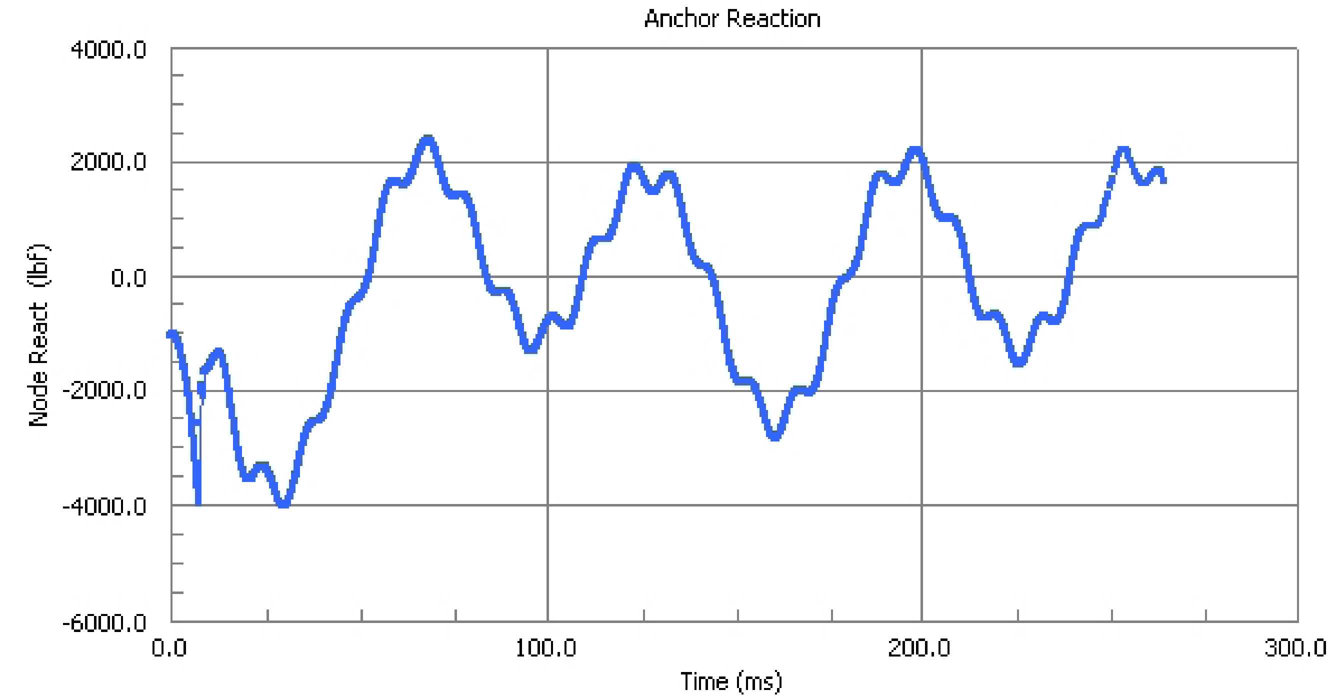
SEQUENTIAL SDOF		
Ductility	Support Rotation (degrees)	Maximum Displacement (in)
1.14	2.26	2.33

Figure 3: Mid-span Results – SSDOF and SDOF

porting elements with a rigid simple support. Removing the flexibility alters how the components and system behave. This change in behavior can be an issue when the negative phase of a blast load coincides with the rebound response of the curtainwall system. This results in a larger rebound response than provided by either SSDOF or SDOF. This is seldom an issue for typically specified blast loads and common curtainwall system geometries. The constructive rebound response is typically an issue with a punched window system, where the natural frequency of the system is closer to overpressure blast duration.

COMPARISON

Figure 3 illustrates how the mid-span deflection of a representative mullion varies with time using SSDOF analysis. The maximum SSDOF deflection calculated is 2.33 inches.



	Ultimate Resistance (lbf)	Sequential SDOF 9lbf)
Reaction	5169	4020

Figure 4: Load to Anchor – SSDOF and Ultimate Resistance

Per SDOF analysis, based upon the methodology outlined in industry standards references [1] and [2], the mid-span deflection is 5.56 inches. SSDOF maximum deflection is 53% less than the SDOF maximum deflection.

Reactions for SDOF [2] and maximum reactions for SSDOF, shown in figure 4, indicate the reaction of SSDOF is 1149 lbf less than the typically required mullion flexural capacity. The difference reflects a missed 28% potential savings in loads to anchor.

CONCLUSION

Sequential single degree of freedom analysis utilizes the energy dissipating and actual strain properties of the major curtainwall components to provide a less conservative analysis of the performance of a curtainwall system. The obvious implication is the specified level of blast resistance may be realized using a lighter and smaller framing cross section, thereby helping to reduce the cost of hardening and providing more freedom to meet the design intent.

REFERENCES

[1] Task Committee on Blast Resistant Design of the Petrochemical Committee of the Energy Division of the American Society of Civil Engineers, 2010, *Design of Blast-Resistant Building in Petrochemical Facilities.* 2nd Ed., American Society of Civil Engineers. Reston, VA., pp 87-88

[2] Mays, G C and Smith P D (eds), 2001, *Blast Effects on Buildings*, Thomas Telford Publications, London, pp.102-105

