IMPROVING THE SAFETY OF BUILDINGS THROUGH AN INNOVATIVE SUSTAINABLE FAÇADE SYSTEM

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Abstract: A building's façade system is the outer layer of a structure that is designed to provide protection to building occupants and contents from external hazards with varying intensity. In the modern world, many structures undergo different types of dynamic loadings such as blast and ballistics, earthquakes, high winds, hurricanes, tsunamis etc. It is a prime importance of the modern structures to sustain those dynamic loadings without excessive damage. Due to the recent trend towards sustainable development, there are more prevalent uses of innovative systems such as the double skin façade systems, which lead to new challenges in assessing the performance of these façade systems under extreme loadings. This paper presents a review of innovative double layer skin façade system with some finite element modeling to assess the behaviour.

Keywords: Double skin façade (DSF) system, finite element (FE) modelling

1. Introduction

Sustainable development has become an increasing priority for building projects worldwide. However, threats of terrorist attacks around the world have also caused building owners and occupants to pay attention to building safety issues.

In recent years, terrorist attacks and natural disasters have increasingly occurred around the world. There are large number of explosions occur within or close to main cities of many countries. These cities are mainly congested with buildings with glazed façade systems. The percentage of injuries caused by the blast is mainly due to the impact of flying fragments. This amount could be as high as 80-90 percent. An example of the magnitude of damage caused by flying fragments is the attack on the Central Bank, Colombo, Sri Lanka in January, 1996. The building was surrounded by few other high-rise buildings with glazed façade systems and more than 90 percent of casualties were due to the impact of flying fragments of the broken glass panels.

Both sustainability and safety measures must be considered within the overall project context, including impacts on occupants and the environment, regardless of the level of protection deemed appropriate. This project aims to develop a secure and sustainable facade system for buildings which will have a significant enhancement over other conventional facades in terms of blast and impact protection and life cycle energy performance. New protective technologies combined with day lighting and climate control systems of building façade will be investigated in this project to: 1) improve the impact and blast resistance of the façade; 2) improve the comfort and performance of building occupants; and 3) reduce greenhouse gas emissions that contribute to global warming. The case study presented in this paper is an attempt to establish the performance characteristics of glazing façade panels in the form of pressure impulse curves. This work is part of an ongoing research project which investigates the behavior and performance of innovative sustainable double skin façades.

2. Background

2.1 Theoretical Blast Wave Parameters

The pressure-time curve of a blast wave is characterized by an abrupt pressure rise when the wave arrives at the target and the following exponential decay into a negative pressure phase. Usually, for windows or façade systems overpressure, P_{so}-P_0 is not the most important criterion [1]. The impulse $i_{s,}$ which is the area under the pressure-time curve is$_s$ of equal importance if not the governing parameter. A typical pressure-time curve of a blast wave is shown in figure 1.

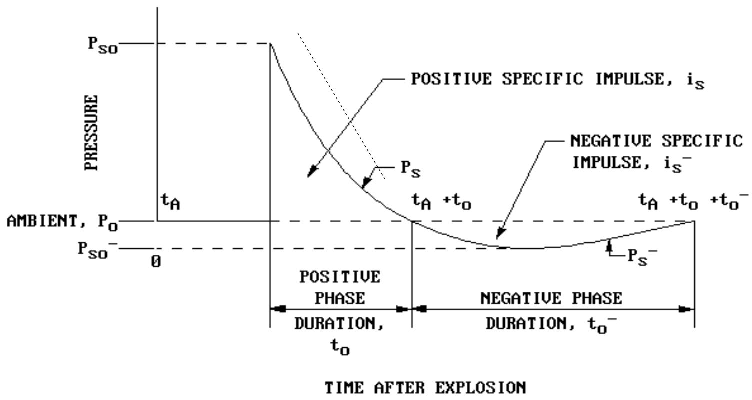
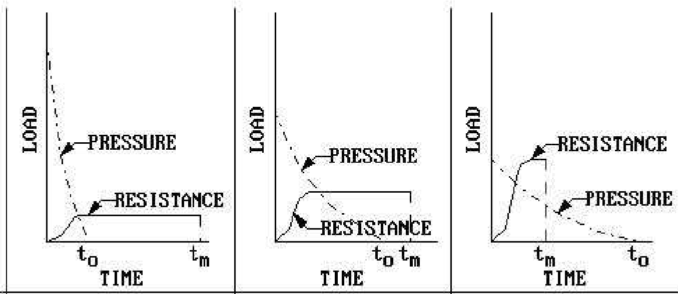


Figure 1 Typical peruse-time variation [2]

Usually, only the positive pressure phase is considered in analysis and the positive pressure phase is idealized as a triangular pressure time history. The negative phase is mostly unimportant in relation to flying debris towards to the protection area. For windows which have to prevent debris on both sides of the construction (e.g. courtyards, buildings close to highly frequented traffic areas, overhead glazing), the negative phase is also important. In addition to the longer duration than the positive phase, the interaction of the negative phase with the pre-damaged structure could be critical in establishing the component performance. In some instances where the structure has a long natural period, the negative phase may decrease the maximal structural deflection. For comparison of simulation with test results, it is necessary to establish the actual time history of the blast pressure including the negative pressure phase.[1]

2.2 Pressure-Impulse curves (iso-damaged curves)

An iso-damage (pressure impulse) curve is a characteristic curve that represents a certain damaged state of an element. A wide range of applications, such as assessment of structural damages and assessment of human survival under blast load pressures, demonstrate the curves' versatility. In general, when subjected to a varying pressure and impulse combination, the response of a structure is governed by the natural period (t_m) of the structure and blast load duration (t_0). Hence, there are three possible scenarios that could occur in the blast event as given below in figure 2.



PRESSURE DESIGN RANGE	HIGH	LOW	VERY LOW
DESIGN LOAD	IMPULSE	PRESSURE-TIME	PRESSURE
INCIDENT PRESSURE	>> 100 psi	< 100 psi	< 10 psi
PRESSURE DURATION	SHORT	INTERMEDIATE	LONG
RESPONSE TIME	LONG	INTERMEDIATE	SHORT
t_m / t_o	$t_m / t_o > 3$	$3 > t_m / t_o > 0.1$	$t_m / t_o < 0.1$

Figure 2 Parameters defining pressure design ranges[2]

Adopting the SDOF approach, the damage or no damage state can be determined based on the maximum displacement criteria. Thus, knowing the maximum allowable displacement, the impulsive and quasi-static asymptote on the pressure impulse curves can be quickly established by applying simple energy conservation principles. Readers can refer to Smith and Hetherington,1994[3] for more details of the development of pressure-impulsive curves. The generic non-dimensional pressure impulse curve is as shown in figure 3.

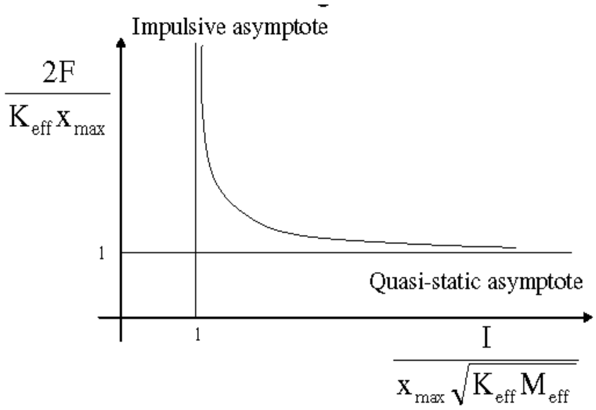


Figure 3 Generic non dimensional pressure-impulse curves.

For each building or construction, it is necessary to specify a permitted hazard level, depending on what the acceptable damage level after an explosion. Standard ISO/DIS 16933 contains hazards rating system from level A- "no hazards" up to level F-"high hazard" as summarized in table 1. The extent of the numerical evaluations shall be based on rating level B to C. For typical windows at level B to C, the following failure modes are common [1]:

- Fracture of glazing
- Crack of PVB interlayer
- Separation of splinters from the rear side of the window
- Pullout from the edges of the frame or failure of structural sealant glazing
- Failure of fittings
- Composite failure in thermally insulated profiles, crack or fracture of fiber-reinforced plastic connections
- Collapse of profile connections
- Local crack or buckling of aluminum profiles due to high plastic strains
- Anchorage failure

Table 1 hazard levels- ISO/DIS 16933

Hazard rating	Hazard rating description	Definition
A	No Break	The glazing is observed not to fracture and there is no visible damage to the glazing system. Calculations via equivalent static loads by diagrams and tables may be sufficient in simple cases.
B	No Hazards	The glazing is observed fracture but is fully retained in the facility test frame or glazing system frame with no breach and no material is lost from the interior surface. Numerical evaluations using nonlinear material laws and plastic deformation capability is possible. Equivalent static systems are not suitable.
C	Minimal hazards	The glazing system is observed to fracture and the total length of tears in the glazing plus the total length of pullout from the edge of the frame is less than 20 percent of the glazing sight perimeter. Also there are no more than 3 perforations or indents anywhere in the vertical witness panel and any fragments on the floor between 1m and 3m from the interior face of the specimen have a sum of total united dimension of 250mm or less. Numerical evaluations using nonlinear material laws and plastic deformation capability is possible. Equivalent static systems are not suitable.
D	Very low	The glazing is observed to fracture is located 1m behind the original location. There

	Hazards	are no more than 3 perforations or indents anywhere in the vertical witness panel and fragments on the floor between 1m and 3m from the interior face of the specimen have a sum of total united dimension of 250mm or less. Exact modeling of failure criteria's of all parts and connections with details are necessary. Extreme fine mesh is required
E	Low hazards	The glazing is observed to be fracture but glazing fragments falls beyond 1m and up to 3m behind the interior face of the specimen and not more than 0.5m above the floor at the vertical witness panel. Also there are 10 or fewer perforations I the area of the vertical witness panel and higher than 0.5m above the floor and none of the perforations penetrate more than 12mmthrough the thickness of the foil backed insulation board layer of the witness panel. Exact modeling of failure criteria's of all parts and connections with details are necessary. Extreme fine mesh is required
F	High Hazards	Glazing is observed to fracture and there are more than 10 perforations in the area of the vertical witness panel and higher than 0.5m above the floor or there are one or more perforations in the same witness panel area with fragments penetration more than 12mm through the thickness of the foil backed insulation board layer of the witness panel. Exact modeling of failure criteria's of all parts and connections with details are necessary. Extreme fine mesh is required.

3. Proposed Double Skin Façade System (DSF)

The DSF system proposed in this project is shown in figure 4. The system consists of the following components:

1) External facade: is a single-sheet laminated glass
2) Shading system: is a venetian blind system, which is normally used for sun-light control. In the project, it is proposed that the shading system will have a dual function for improving both sustainability and safety. Firstly, it will be coated with amorphous silicon photovoltaic material to become a renewable energy source. Secondly, the venetian blinds will also be designed as a cable catcher for catching glass fragments from the external facade.
3) Internal façade: normal glazed windows.
4) Ventilation system: the ventilation system will regulate the air movement in the cavity using solar energy generated from the PV blind system.
5) Climate sensing and control system: Automatic control of the ventilation and opening of the shading system will be done based on the sensor system which can monitor temperature and solar radiation as well as track sun position.

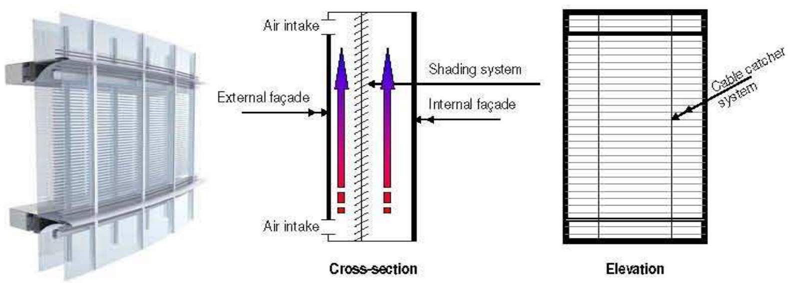


Figure 4 Double skin facade systems

3.1 Energy performance and life cycle energy of DSF systems

The aesthetic desire for fully glazed building envelopes poses serious challenges to building designers. Considerable research has been conducted into the thermal behaviour of double skin facades in the past decade. A search of just one leading international journal on building performance shows more than 20 papers investigating this topic in the last decade. The overwhelming emphasis of this research has been directed to reducing energy consumption. The variations in double skin façade designs (box, shaft, corridor and multi-storey) [4] means that comprehensive and reliable design guidelines and software which can be used by building designers to evaluate options are still not available. The embodied energy implications of a DSF also need to be balanced against any cooling, heating or lighting energy savings that it provides. Further research is required to provide these tools and life cycle energy analysis of this complex facade system.

3.2 Energy performance and life cycle energy of DSF systems

The main challenges in blast protection of DSF systems are: 1) how to dissipate as much energy of the blast wave as possible after the failure of the external facade; 2) how to stop the flying fragmentation from the breakage of the external facade. The research team at the University of Melbourne has been involved in full scale blast trials in Woomera from 2002-2007 [5]. It was observed in those trials that the ultimate failure mechanism of glass is not well understood particularly at the edges. Recent testing (Woomera) has shown several mechanisms including:

1. PVB tearing at the glass-frame edge
2. PVB pull-out between the laminated glasses leafs at the glass-frame edge.
3. Through thickness cracking of the inner leaf of the glass at the glass edge.

As these mechanisms are still unpredictable, where glass is designed to its limits, there is a high degree of risk that the glass at its ultimate failure displacement may not perform as designed. Under blast pressures, it is likely that the panels would be dislodged as a whole and propelled into the structure as shown in figure 2. Laminated glass is commonly used as the external skin of the façade system, which underlines the importance of establishing the projectile borne out of the external skin of the DSF system.

4. Analysis Procedure & FE Modeling

4.1 Analysis Procedure

The FE modelling approach is used to develop the P-I curves of both the internal and external layers of the façade system. Once the P-I curves of both external and internal layers are obtained, the P-I curves of both the external layer and the curtain wall could be used as a failure criteria in computational fluid dynamic (CFD) modelling. The detailed simultaneous analysis process is presented in [6].

In this exercise, two models were built and analysed with the LS-DYNA FE code. The DSF system consists of one layer of an internal skin and one layer of an external skin. For the purpose of this preliminary study, shading system was excluded and the external layer of the glazing system is limited to non-laminated glass panel. The internal skin of the case study structure consists of one single framed glazing unit that is embedded into the ceiling and floor of a retail atrium. A glass panel with typical dimensions of 3 m tall, 1.2 m wide and 8 mm thick was selected. The frame units are typically bolted to the support structure at intervals of approximately 900 mm. Thus, the translational degrees of freedom of the models were constrained at the bolt locations, as illustrated in Figure 8(a). Meanwhile, the external layer covering the vision panel of the system is typically a 2.4 m tall, 1.2 m wide and 10 mm thick glass panel. The external skin façade system is typically supported at four locations with bolt-like devices, which allow rotation but restrict the translational movement of the glass panel. A simplified schematic of the external skin of the DSF system is shown in Figure 8(b).

Shell and eight-node solid elements were used to model the glass panels and framing system, respectively. The models were built as quarter models with two axes of symmetry. The framing system of a window glass unit normally involves a complex interaction between the head-subhead, sill-subsill and the actual panel itself. However, the internal skin of the DSF system model simplifies this interaction into three elements: the aluminium frame, the sealant material, and the glass panel itself. The translational degrees of freedom of the frame were restrained only at the likely bolt locations. The simplifications were made based on preliminary parametric studies and comparison between the responses of the typical glazing unit model and the simplified glazing unit model. The simplifications incorporated were necessary due to the high computational demand of the typical full-blown model [6].

(a) (b)

Figure 5 FE model of external skin of the DSFS

4.2 Material Constitutive Models

In the analytical model, three different material types need to be defined. The aluminium frame in the glazing unit exhibits linear elastic with ductile post yield behaviour. An isotropic elastic plastic material model, which is capable of modelling material plasticity, is used. An elastic material model was used for the structural sealant model. The cost-effective elastic material model is used to simulate the glass panel behaviour in this exercise.

4.3 Blast Load Application

In the FE analysis phase, the in-built CONWEP function in LS-DYNA was used to randomise the blast pressure-impulse. The blast pressures, computed using the CONWEP function, were applied as shell surface pressures. The empirical modelling approach, CONWEP[7], can provide a blast pressure estimate with a reasonable degree of accuracy[5]. However, it must be noted that CONWEP could not simulate the negative phase of the blast pressures. It was acknowledged that the negative phase of the blast pressures might have an influence on the glass panel response. Thus, the effect of the negative phase on the glass panel response is subject to further research in the project.

4.4 Pressure-Impulse Curves

The characteristic P-I curves of the internal skin and the external skin of the façade system are shown in Figure 9.

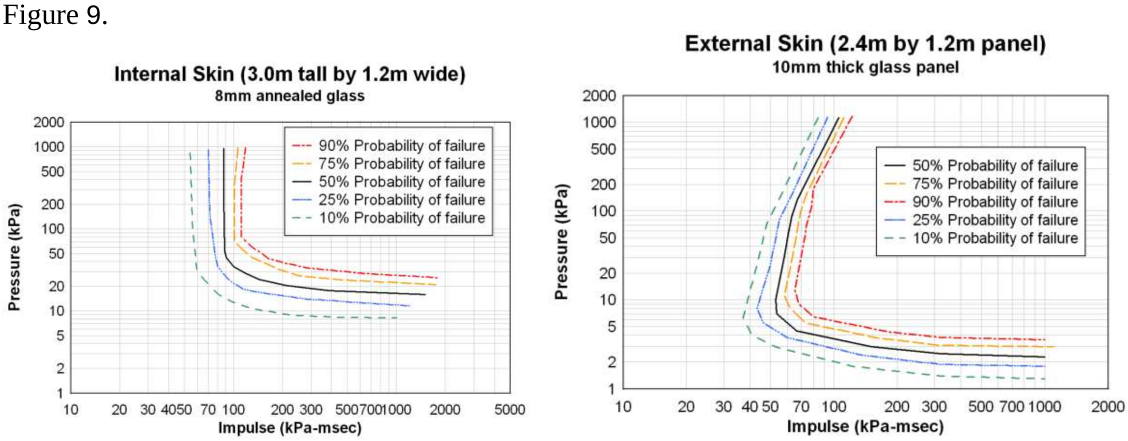


Figure 6 P-I curves for internal and external skin façade in DSFS

4.5 Computational Fluid Dynamics Phase

In this phase, the CFD code, Air3D [8] which is capable of modelling the blast wave-structure interaction to a significant degree of accuracy[9], was utilised to derive the overall performance of the façade system. In this analysis, the failure criterion of the overall DSF system was defined as the breach of the internal skin of the façade system.

After obtaining the P-I curves representing the failure criteria of the internal skin and the external skin of the façade system, the failure criteria of the external skin and the internal skin were used in the CFD analysis to establish the combined fragility of the DSF system. The façade layers are modelled as frangible panels with the P-I curve as a failure criterion in the CFD model. The CFD model was built to simulate a condition similar to a blast trial environment, whereby both layers of the façade system are embedded into two rectangular test modules.
The CFD analysis approach is capable of tracking the blast pressure and blast impulse applied onto the façade layer. Hence, the response of DSF system can be defined in three stages. These are:

- Stage 1 – Blast pressure arrival at the external façade surface.
- Stage 2 – External façade response. In this stage, the failure or non-failure of the external façade layer is determined by comparing the P-I values imparted on the external façade system against the P-I curve as a failure criterion. If failure occurs, the blast wave will propagate into the structure, leading to a Stage 3 response.
- Stage 3 – Internal façade response. In this stage, the failure or non-failure of the internal facade layer is determined by comparing the P-I values imparted on the internal façade against the internal façade's P-I curve as a failure criterion.

One fragility curve only exhibits the vulnerability of the façade system to one particular charge weight. Thus, several sets of analysis need to be carried out to assess the vulnerability of the same façade system subjected to different threat charges. In a set of analysis, the blast charge weight is kept constant throughout, whilst the stand-off distance is varied. For example, if a charge weight of 25 kg TNT with a 24 m stand-off distance is required to induce a 50% failure probability on the curtain wall layer, a point with an abscissa of 24 m and an ordinate of 50% can be recorded on the fragility chart. The 25 kg charge weight fragility curve is developed by repeating the analysis process to obtain the stand-off distances required to induce a 10%, 25%, 50%, 75% and 90% probability of failure criteria.

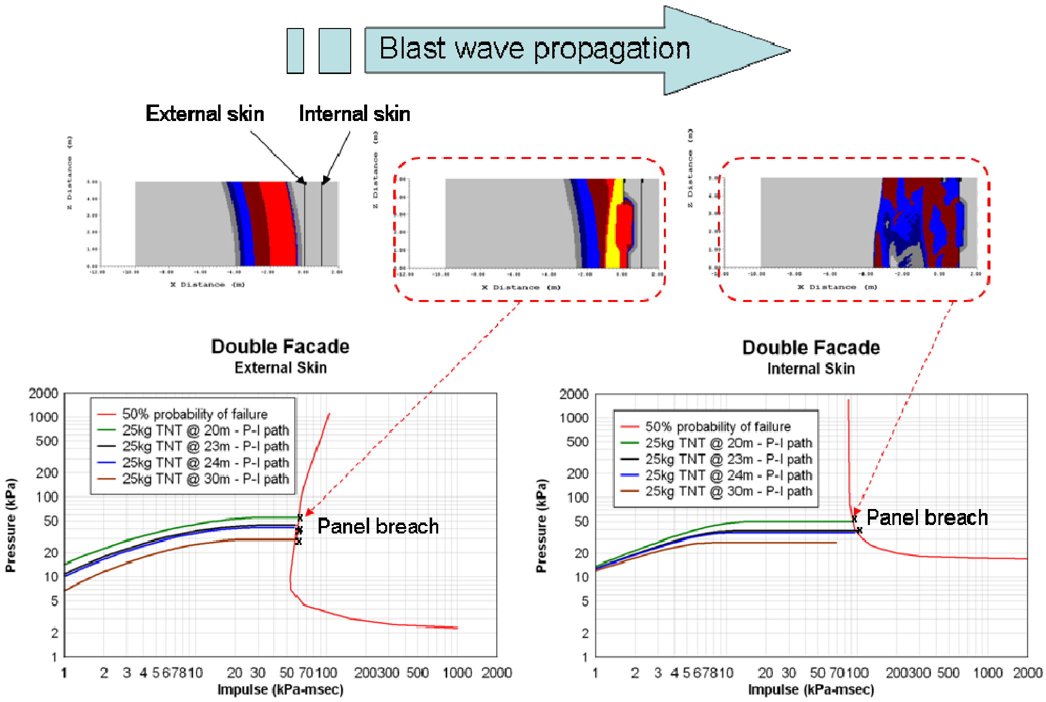
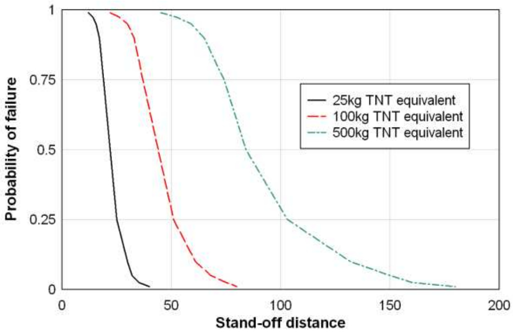


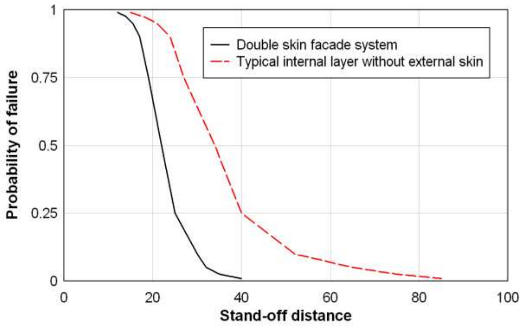
Figure 7 Double skin façade response

5. Results and Discussion

The fragility of the DSF system is shown in figure 11(a). In addition to providing an early indication of the performance of the DSF system, the analysis results indicate a marked improvement of façade system blast performance when a sacrificial external layer is used in the system (i.e. the DSF system). The blast performance improvement is illustrated in figure 11(b).



(a)



(b)

Figure 8 (a) Fragility curves for DSF system, (b) Comparison between façade systems with external layer and without external layer for 25 kg TNT equivalent charge

6. Concluding Remarks

The Doble Skin Faceade system is envisaged to be a very popular system in the future due to the trend in the construction industry towards sustainable design and construction. This paper presents an attempt to quantify the implications of future adoption of this DSF system on the blast performance of the overall façade system. Performance indicators for preliminary DSF system, in the form of P-I and fragility curves, were developed in this exercise. A particular failure criterion, tensile fracture of the glass panel, was adopted in this analysis. However, the framework developed in this exercise can be used in conjunction with different failure criteria. The fragility curves developed for the DSF system indicate that the sacrificial external skin would contribute towards increasing the overall façade performance. The findings from this exercise also indicate that the performance of the overall system can be improved by adopting an external skin layer that is capable of dissipating a significant proportion of the blast energy. This preliminary analysis is based on the assumption that the internal skin failure is governed by the blast pressure propagation. It must be noted that two components, namely, the PVB laminates and the cable catcher system were left out in the analysis. Further studies to establish the effect of the PVB laminates and the shading system in the DSF system is currently under way.

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