Investigation on Concrete Fins as Blast Resistors in Buildings

K. Baskaran and R. M. B. Prasad

Abstract: Designing structures against blast loading is becoming more and more important as the number of terrorists attacks are increasing day by day. It is necessary to protect the structures against a credible blast load to ensure the safety of the occupants. In this context, blast resisting facades are incorporated in buildings to avoid the blast pressure waves entering into the building as the highest damage is done by the pressure waves when compared with the fragments moved by an explosion. Pressure waves could damage the critical elements and it may lead to progressive collapse of the structure. This study investigated the behaviour of concrete fins that can be used to enhance the blast resisting capacity of facades. Blast pressure loads were calculated when varying the fin spacing to evaluate the capacity of fins having different section properties. Occupancy levels such as immediate occupancy, life safety and collapse prevention were used to identify the structural performance. Material nonlinearity, material strength enhancement with higher strain rates and nonlinear loading were considered in this study and analysis was done using the Sap2000 software. Weight of blast materials, standoff distance and fin spacing were considered to create different blast loads while fin sizes and there reinforcement arrangements were also varied to create different load cases. Charts were prepared for different concrete sections based on the occupancy levels, blast pressure loading and reinforcement ratio. It enables to identify the most suitable sections that are required as structural elements to be behaving in the required occupancy level for a given scale distance.

Keywords: Blast pressure loads, Concrete fins, Material nonlinearity, Progressive collapse

1. Introduction

Terrorist attacks are increasing globally, and it appears that there is no ending. Therefore, it is necessary to protect structures from terrorist attacks. However, the protection is not an absolute measure to issue and there should be different levels of defensive systems, which also minimize the cost of system. Protection can never offer a guarantee of safety. High level of protection will also increase the cost of the construction and could be a waste of resources. However, it is very important to take measures to protect most vulnerable structures against blasts. It is learnt that the structures, which will be constructed in the future could be designed for at least a credible blast load. There are many examples in the past that proves the above.

Attack to the Central Bank of Sri Lanka on 31 January 1996 is believed to be the largest bomb blast occurred within the country. About 85 people died and more than 1500 people were injured. After observing the images of the damaged structure, it can be understood that designers had not predicted such event at the design stage. The building was severely damaged although it did not collapse. Main causes of damage are due to the blast pressure and subsequent fire occurred inside the building. This could be due to lack of defensive system that bears the blast pressure.

Different types of defensive systems have been introduced to avoid the collapse of the structures due to the failure of load carrying elements and to avoid the fragments entering into the building. One such defensive technique is enhancing the load resisting capacity of facade. Most commonly, facades are constructed from brick, concrete and glass. Different techniques are used to increase the load carrying capacity of facades constructed from above materials. When there is no defensive system to protect the axially loaded elements, it could lead to progressive collapse.

Brick walls are strengthened by introducing cross wall, increasing the width of the wall and adding steel plates where it fails. Glass walls are modified by adding fins while windows are modified by laminating membrane.

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Facades act as defensive elements and they do not allow the blast waves entering into the building. As a result, load carrying elements such as concrete columns and walls will not be damaged, and risk of arising progressive collapse is minimal. Concrete facades can resist very high blast loadings. As the concrete is weak in tension, it is required to provide large sections or increase the area of reinforcement to accommodate a higher blast pressure. As an alternative, load carrying capacity of concrete facades can be increased by providing concrete fins at a determined spacing according to the loading on structure. In this research, load carrying capacity of the concrete fins, according to their spacing and area of reinforcement, are studied and failure criteria will be defined by specifying whether each element is on the state of immediate occupancy, life safety and collapse prevention.

2. Literature Review

2.1 Blast Phenomenon

A blast is a sudden release of energy due to the reaction of explosive materials. Blast effects of an explosion are in the form of a shock wave composed of a high intensity of shock front which expands outward from the surface of the explosive into the adjoining air. As wave expands, it decays in strength, lengthens in duration and decrease in velocity. This phenomenon is caused by spherical divergence as well as by the fact that the chemical reaction is completed, except for some after burning associated with the hot explosion products mixing with the surrounding atmosphere.

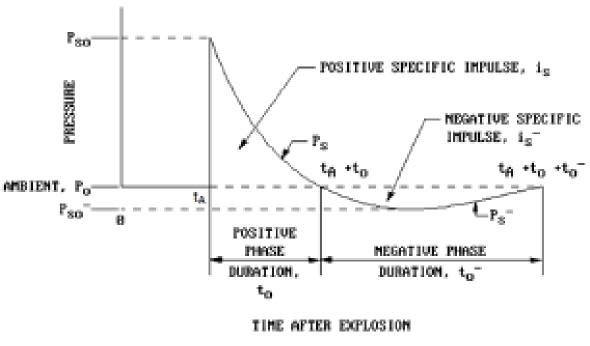

Figure 1- Variation of Incidental Pressure with Time [1]

A blast wave has two phases, namely they are positive phase and negative phase, and negative phase is less significant compared to the positive phase due to its magnitude [1]. Sudden increase of incident pressure at a point away from the blast reduces with time and it reaches to zero pressure as illustrated in Figure 1. After it reaches zero, wave moves into the negative phase producing a negative pressure.

Variation of the blast pressure, P(t), with the incidental pressure, P_{so}, with the time is indicated in the following equation.

$$P(t) = P_{so}(1-t/t_0)\exp(-bt/t_0) \qquad (1)$$

Magnitude of the reflected blast pressure, which is considered for design of structures, is significantly higher than the incidental pressure due to the ground reflection when blast occurs near the ground level. Mach reflection is the meeting of incident wave with the reflected wave [2]. The wave front created is called the Mach stem. Heights of the Mach stem increases when it moves away from the blast creating a planer wave in vertical direction. In addition, formation of Mach stems makes uniform pressure over the façade of the building as indicated in the Figure 2. Application of uniform blast pressure over the surface of the façade depends on the distance to the blasting location from the structure.

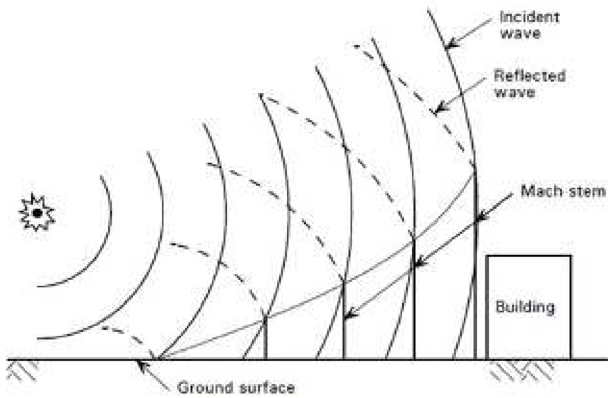

Figure 2 – Wave Pattern of Mach Stem [2]

2.2 Scale Distance

Magnitude of the incidental pressure and blast wave characteristics depend on the term scaled distance which is calculated by taking into account the weight of the blast material (W) and Standoff distance (R), which is the distance from the structure to where the blast occurs. Relationship between the standoff distance and weight of blast material presented by Hopkinson [3] and Cranz [4] is used most commonly to evaluate the blast loadings.

$$Z = R / W^{1/3} \qquad (2)$$

Most challenging part of the analysis of a structure for blast loading is the estimation of the blast loading accurately. Due to the high uncertainty in the weight of the blast material, accurate evaluation of the weight is a very difficult task. Manmohan, et al. [5] in their study on comparison of blast wave parameters, found that there is a wide variation in peak positive overpressure when Z<1 m/kg$^{1/3}$. Thus, UFC 3 – 340 – 2, (2008) [1], which is published by Department of Defence, United States of America, was used in this study for evaluation of blast pressure.

2.3 Evaluation of Blast Pressure

Parameters of the positive and negative phase was evaluated from the graphs given in the UFC 03-340-02 (2008) [1].

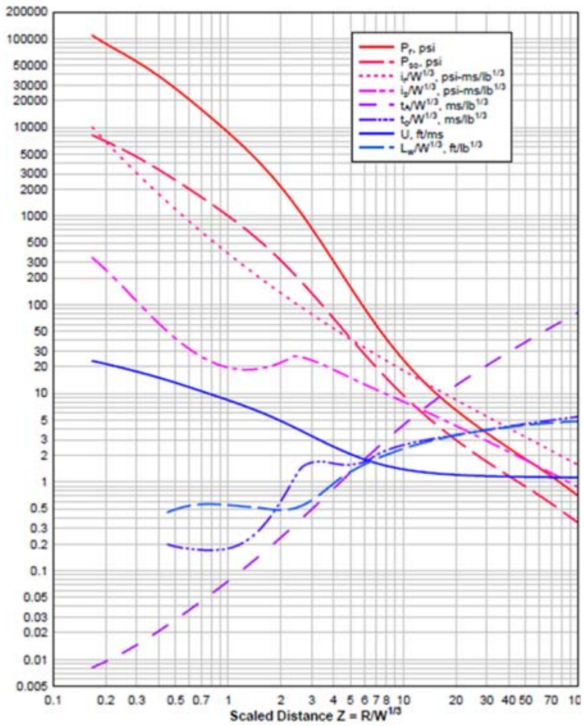

Figure 3 – Positive Shock Wave Parameters for a Hemispherical TNT Explosions on the Surface at the Sea Level [1]

Positive and negative phase parameters were evaluated from Figure 3 and Figure 4 respectively. Simplified, variation of blast pressure given in UFC 3-340-2 (2008) [1] is used in this study for analysis purposes.

2.4 Material Behaviour

Linear range of the material are used for most of the analysis. However, at research level, most of the analysis use the nonlinear range and get the benefits of it. The book Blast Effects on Buildings [6] provides guide to enhance the material properties depending on its characteristics. Table 1 indicates the material enhancement

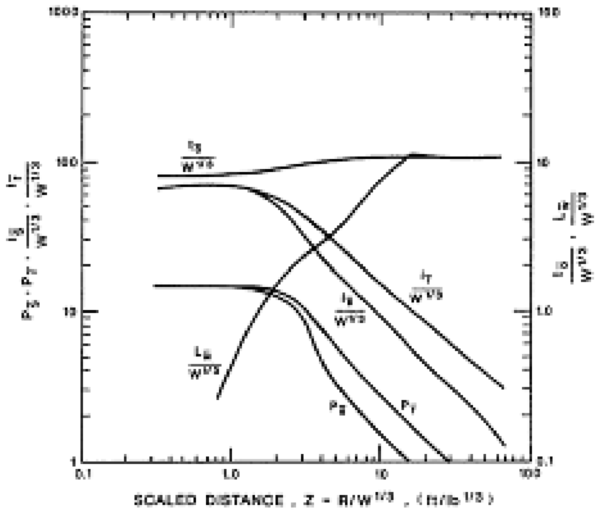

Figure 4 – Negative Phase Shock Wave Parameters of a Hemispherical TNT Explosion on the Surface at the Sea Level [1]

Factors extracted from the book Blast Effects on Buildings, which were considered in this study. Material model proposed by Kent and Park [7] for confined concrete was used in this study.

Table 1 – Material Enhancement Factors [6]

Type of stress	Concrete	Reinforcing bars		Structural steel	
	f_{dcu}/f_{cu}	f_{dy}/f_y	f_{du}/f_u	f_{dy}/f_y*	f_{du}/f_u
Bending	1·25	1·20	1·05	1·20	1·05
Shear	1·00	1·10	1·00	1·20	1·05
Compression	1·15	1·10	—	1·10	—

* Minimum specified f_y for grade 50 steel or less may be enhanced by the average strength increase factor of 1·10.

2.5 Facades and their Development

Brick, concrete and glass are used most commonly as materials to construct facades. Concrete is most commonly used to protect the structures from blast-loads as a concrete structural element has higher failure load compared with brick in flexure. However, when blast occurs near the structure, facades have to carry very high impact loads. In modern construction, different techniques are used to improve the capacity of concrete facades. One of such methods is providing concrete fins. Concrete fins can be introduced in between the floors for reducing its spans and it acts as a flexural element (beam element) to carry the blast pressure loads transferred from the façade wall. It enhances the blast resisting capacity of the façade wall and adjusting the spacing of fins, economical construction can be done.

Limited numbers of guidelines are available to design blast resisting facades. Ngo et al. [8] have done study on Blast Loading and Blast Effects on Structures. When the blast occurs far away from the structure, blast pressure on façade becomes uniform in part of area of the facade due to Mach reflections. Uniform blast pressure which varies with the time was considered in this study. Analysis of concrete wall under the blast loading has been done by Tiwari et al. [9] for different shapes of concrete walls with and without steel plates and different arrangement of the walls such as "L" shape and "U" shape. Oswald and Bazan [10] have studied the performance and blast design for non-load bearing concrete panels. This study has identified that reinforced non-load bearing panels that includes solid concrete panels and insulated sandwich panels with conventional and pre-stressed reinforcement can be designed to resist blast loadings and their recommendations are based on the tests of precast panels.

Based on the study limitations in the simplified approach in assessing performance of façade under blast pressure by Lumantarna et al. [11], it can be identified that factors such as higher mode shape of vibration and the negative phase of a blast pressure have an influence over the performance of the panel. Further, it can be implied from the analysis results that neglecting negative phase in the analysis may lead to un-conservative performance prediction of the dynamic response region. In addition this study highlights the importance of taking into account the negative phase of the blast pressure, especially in the analysis of materials or structural system with limited or no ductility.

2.6 Performance Based Design

In performance based design, performance of the structure is evaluated with sophisticated calculations or structural analysis. Guidelines given in FEMA 356 [12] are used in the study to define the performance levels. Plastic rotation angle is considered to define the performance levels and performance level for flexural elements such as column and beams are given separately in FEMA 356. Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) limits as indicated in the Figure 5 was used to identify the structural performance. Further, Figure 5 shows the performance levels of a structure with respect to global displacement. This is done based on the damage level to the structure. Depending on the occupancy level that the structure to be behave in the event of blast, structural designs are carried out.

When an element is considered for performance based design, its plastic rotation is considered.

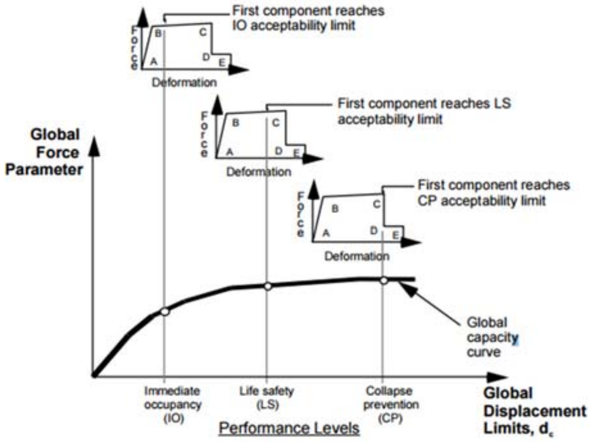

Figure 5 – Performance Levels [12]

Each occupancy level can be defined with respect to the hinge rotation. Sap2000 software provides comprehensive guideline to define each performance level. Point B in the Figure 5 indicates the yielding and no deformation are considered up to the point B. Beyond the point B the rotation of the hinge is considered in the analysis to define the occupancy levels.

3. Methodology

Modelling of the concrete fins was done with SAP2000 software. Concrete fins were modelled as frame elements and they were defined with section designer in SAP2000 to get the moment curvature curve accurately. Fins were modelled with frame elements, different sizes of concrete fins, different fin spacing and different reinforcement ratios were considered. Figure 6 indicates the typical arrangement of fins. Fins are supported in the perimeter beams.

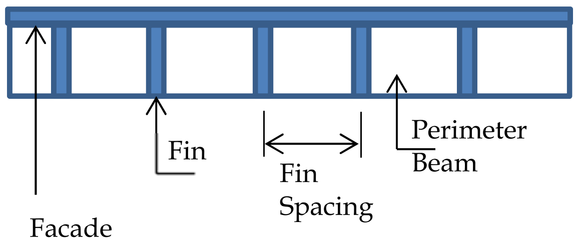

Figure 6 – Arrangement of Fins

Different sections having reinforcement ratios as shown in the Table 2 were analysed in this study. Analysis cases were created by varying the section and the blast pressure loads. Standoff distances of 10m, 25m and 50m and weight of blasting materials 10kg, 25kg, 50kg, 100kg, 200kg, 300kg and 400kg were considered to evaluate blast pressure loads act on the façade. Evaluation of the blast pressure loads were done as specified in the UFC-03-340-2, [1].

Table 2 - Different Analysis Cases

Spacing	1m	2m	3m
Section	150x500, 150x600, 150x800	150x500, 150x600, 150x800	150x500, 150x600, 150x800
R/F	8T10, 8T12, 10T10, 10T12, 12T10, 12T12, 16T12		

Instead of exponential variation of blast pressure at a given time, linear variation was considered in this study as indicated in the Figure 7. Relevant parameters of the simplified pressure profile for each load cases created by varying the weight of the blasting materials and standoff distance, were found from the Figure 3 and Figure 4.

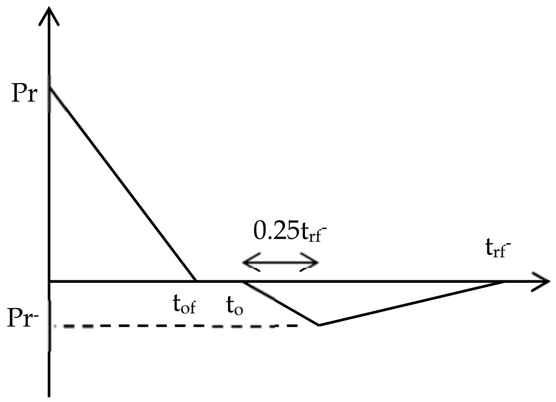

Figure 7 – Simplified Variation of Blast Pressure

Material model of Kent and Park [7] was considered to model the behaviour of concrete. Material model was evaluated based on the section properties and concrete properties. Further, enhancement of the characteristic strengths due to the higher rates of changes of strains were taken into account when material model is evaluated. Dynamic characteristic strengths were evaluated as suggested by [6] by multiplying yield strength by 1.2, tensile strength by 1.05 and cube strength by 1.25.

Failure of elements were defined with the plastic rotation of hinge. Occupancy level, which are based on the plastic rotation of the elements; immediate occupancy (IO), life safety (LS) and collapse prevention (CP) were considered in this study to define a failure mode of an element. It represents the damage level to the element in the form of occupancy level. Hinge properties were defined as specified in the FEMA 356 [12].

4. Results

Categorization of the element based on the occupancy level that they behave when the blast pressure loads were applied, was done for ease of identifying the element sizes and their spacing at the initial stage of the designs. Variation of the bending moment with the time, plastic rotation of the hinge were recorded when the elements were categorized.

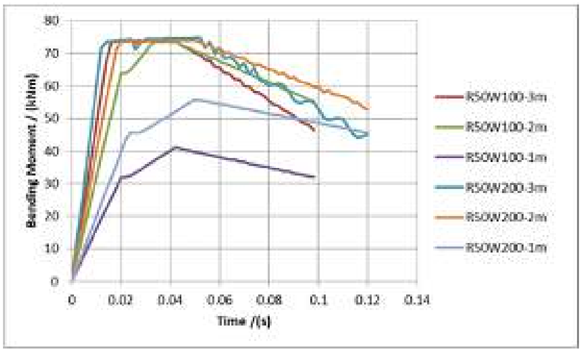

Figure 8 – Variation of Bending Moment (150x500, 8T10)

Variation of the bending moment with the time of fin having dimensions 150x500mm and eight numbers of tor steel bars of diameter 10mm indicated in Figure 8 for load cases of standoff distance of 50m and weight of the blasting materials 100kg and 200kg. In addition to the evaluation of the bending moments, occupancy levels of the hinge was also recorded as indicated in the Table 3.

Table 3 – Status of Hinge (150x600, 10T10)

Fin	Load Case	Fin Spacing	State of the Hinge
150x600 10T10	R10W10.3m	3	IO
	R10W25.2m	2	LS
	R10W25.3m	3	CP
	R10W50.1m	1	LS
	R10W50.2m	2	>CP
	R10W50.3m	3	>CP
	R10W100.1m	1	>CP
	R10W100.2m	2	>CP
	R10W100.3m	3	>CP
	R10W200.1m	1	>CP
	R10W200.2m	2	>CP
	R10W200.3m	3	>CP
150x600 10T10	R25W100.3m	3	IO
	R25W200.2m	2	IO
	R25W200.3m	3	LS
	R25W300.2m	2	IO
	R25W300.3m	3	LS
	R25W400.2m	2	LS
	R25W400.3m	3	CP

(R – Standoff distance, W – Weight of blasting materials)

Status of the hinge for each element were recorded similarly as indicated in the Table 3. Thus, it was possible to identify the element is in which occupancy level for given blast loading. After identify the occupancy level to be reached by the element in an event of blasting, arrangement of the reinforcement and size of fin can be selected depending on the blast pressure. Charts that enable the designer selecting element sizes depending on the scalded distance, was prepared as indicated in the Table 4 and Table 5 for fin sizes 150x500mm and 150x600mm. Load case in Table 4 to Table 6 are represented with R (standoff distance), W (weight of the blast materials) and fin spacing in metres.

Table 4 – Summary of Analysis Results of 150x500mm concrete Fin

8T10	IO	R10W10.1, R25W25 R25W50, R25W100 1&2, R25W200.1, R25W300, R50W100, R50W200, R50W300, R50W400, R10W10.2, R10W25.1, R25W400.1
	LS	R10W10.2&3, R10W25.1, R25W100.3, R25W200.2, R25W300.2, R25W400.1
	CP	R10W50.1, R25W200.3 R25W400.2
8T12	IO	R50W100, R50W200 R50W300, R50W400 R10W10.2, R10W25.1
	LS	R10W10.3, R10W50.1 R25W100.3, R25W200.2 R25W200.3, R25W300.2
	CP	R10W25.2, R25W400.2
10T10	IO	R50W100, R50W200 R50W300, R50W400 R10W10.2, R10W25.1 R25W400.1
	LS	R10W10.3, R25W100.3 R25W200.2, R25W300.2
	CP	R10W50.1, R25W200.3
10T12	IO	R50W100, R50W200 R50W300, R50W400 R10W10.2, R10W25.1 R25W400.1
	LS	R10W10.3, R10W50.1 R25W100.3, R25W200.2 R25W200.3, R25W300.2
	CP	R10W25.2, R25W400.2

Elements that were beyond the collapse prevention limit for fin sizes 150x500mm and 150x600mm were analysed by increasing the section dimensions to 150x800mm and the analysis results are tabulated in Table 6. All the elements considered in this study have reached life safety limit or immediate occupancy level with the increase of dimensions of the fin and its reinforcement ratios to 150x800 and 16T12 respectively.

Table 5 – Summary of Analysis Results of 150x600mm Concrete Fin

10T10	IO	R10W10, R10W25.1 R25W25, R25W50 R25W100 R25W200.1&2 R25W300.1&2
	LS	R10W25.2, R10W50.1 R25W200.3, R25W300.3 R25W400.2
	CP	R10W25.3, R25W400.3
10T12	IO	R10W10, R10W25.1 R25W25, R25W50 R25W100 R25W200.1&2 R25W300.1&2
	LS	R10W25.2&3, R10W50.1, R25W200.3 R25W300.3, R25W400.2 &3
	CP	R10W100.1
12T10	IO	R10W10, R10W25.1 R25W25, R25W50 R25W100 R25W200.1&2 R25W300.1&2
	LS	R10W25.2&3, R10W50.1, R25W200.3 R25W300.3, R25W400.2 &3
	CP	R10W100.1
12T12	IO	R10W10, R10W25.1 R25W25, R25W50 R25W100 R25W200.1&2 R25W300.1&2
	LS	R10W25.2&3, R10W50.1, R25W200.3 R25W300.3, R25W400.2 &3
	CP	R10W50.2, R10W100.1

Table 6 – Summary of Analysis Results of 150x800mm Concrete Fin

16T12	IO	R10W25.2, R10W25.3, R10W50.2, R10W100.1, R25W300.3, R25W400.2, R25W400.3
	LS	R10W50.3, R10W100.2, R10W200.1
	CP	-

5. Discussion and Conclusions

Analysis of concrete fins that carry the loads transferred from the facade was done in this study. Concrete fins are used as structural elements to carry the blast pressure to the main structure without damaging the structural elements that carry the vertical loads. It is the common practice to decide the required performance level that the structure to be behaving during a blast before starting the preliminary design work. Thus, structural engineer carryout the design work in a way that the structure behaves in particular occupancy level. Based on the analysis results and when the blast pressure is known, designer can select the size of the fin and with its reinforcement arrangement based on preferred spacing of fins for required occupancy level.

All the load cases considered as the blasting occurs at a distance of 50m (R = 50m) from the structure, were in the immediate occupancy level as indicated. However, with the standoff distances 10m and 25m fins behave in life safety limit, collapse prevention limit while some of the load cases have passed the collapse prevention limit. Around 50% of the load cases, where the standoff distance considered as 10m with fin size 150x600, had passed the collapse prevention limit creating a situation where it required to further increase the stiffness of fins by increasing the percentage of reinforcement or size of the fins. When fins of 150x800mm having 16T12 were analysed, all the load cases were in the Life Safety Limit, moved into Immediate Occupancy Level while some of the load cases had passed the Collapse Prevention Limit moved into the Life Safety Limit. Significant improvement of the occupancy level is observed for fin 150x800mm (16T12).

The load cases created with standoff distance of 25m were identified as manageable with selected fin spacing. Load cases with smallest section dimensions (150x500mm) and reinforcement (8T10) had reached to all the occupancy levels, while more than 50% of the cases considered in this study were in the immediate occupancy level. With the increase of the reinforcements and the section dimensions, maximum limit reached by load cases were life safety limit as shown in Table 4 to Table 6 demonstrating the idea that if a blast occurs at standoff distance of 25m, it can be managed with the maximum section dimensions (150x600mm) and reinforcements (12T12). Thus, distance of 25m can be considered as a case where fins are not collapsing and lives are safe.

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