Structural Response of Steel Columns to Long-Duration Blast Loading – The Influence of Section Orientation

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1. BACKGROUND

Introduction

Steel columns are found extensively in the construction of single to multi-storey framed structures. Explosive blast loading has the potential to exert lateral forces on columns far higher than their capacity, causing permanent deformation.

A number of recent large-scale industrial accidents such as the 2005 Buncefield oil refinery explosion, the 2013 West Texas fertiliser factory explosion and the 2015 Tianjin explosions highlight a growing need to understand the response of structural elements to long-duration blasts [1]-[3].

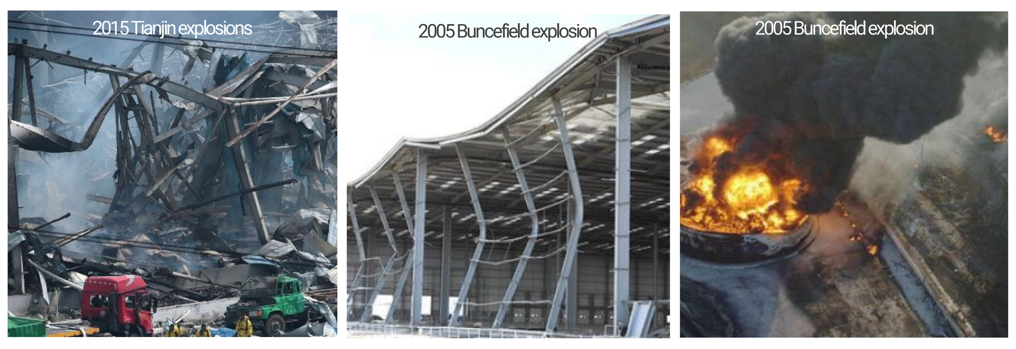
Defining 'long-duration' blasts

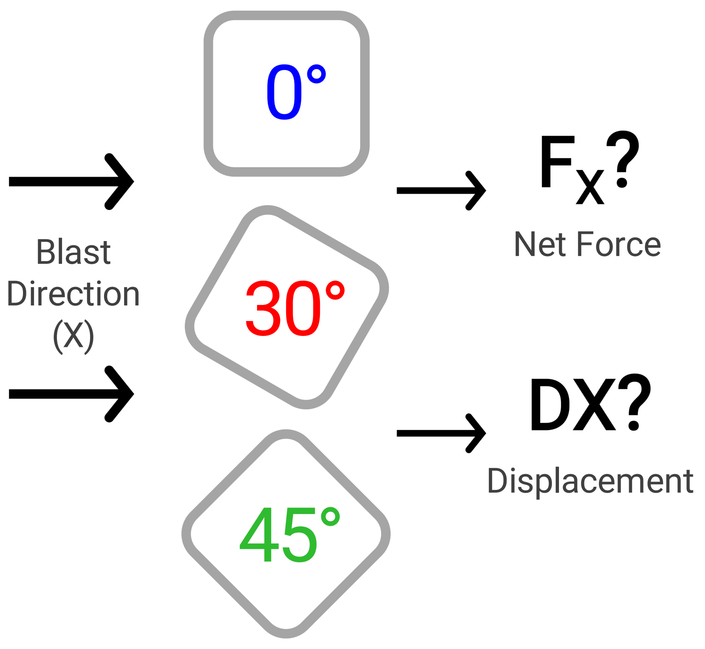
Long-duration blast waves are typically defined by positive pressure durations over 100ms, developing in the later stages of shock wave propagation i.e. in 'the far field' from the source of detonation and are associated with:

- Non-trivial dynamic pressures
- Damaging drag loading
- Very large impulses

How are long-duration blasts caused?

Blast waves reaching a later stage of propagation with sufficient energy to cause structural damage are characteristic of large-scale explosive events. In the modern world, these are commonly caused by hydrocarbon vapour cloud explosions (VCE) at petrochemical facilities due to the nature in which volatile hydrocarbons are stored, equating to large amounts of potential energy.





How does column section orientation influence blast loading and structural response?

Context

Long-duration blast pressures enable greater kinetic mobilisation of air particles behind the shock front, thereby generating dynamic pressures (blast winds) capable of exerting significant drag loads on slender structural elements such as columns. Structures and their constituent column elements can be subjected to blast waves from various angles of incidence (section orientations) depending on the location of detonation; this may arise in industrial operations where explosive materials are confined to certain areas of a facility.

Motivation

Characterising blast drag loading can be complex, typically requiring approximation using drag coefficients for which there is limited availability or provision for different section orientations [4], [5]. Blast resistant design manuals and simplified analytical methods for calculating structural response are generally limited to considering blast response about orthogonal axes, with no prior studies or guidance pertaining to the response of column elements at intermediate, oblique section orientations.

Aim

To investigate and quantify the influence of square hollow section (SHS) column orientation on blast loading, transient dynamic response and final damage state.

2. EXPERIMENTAL METHODOLOGY

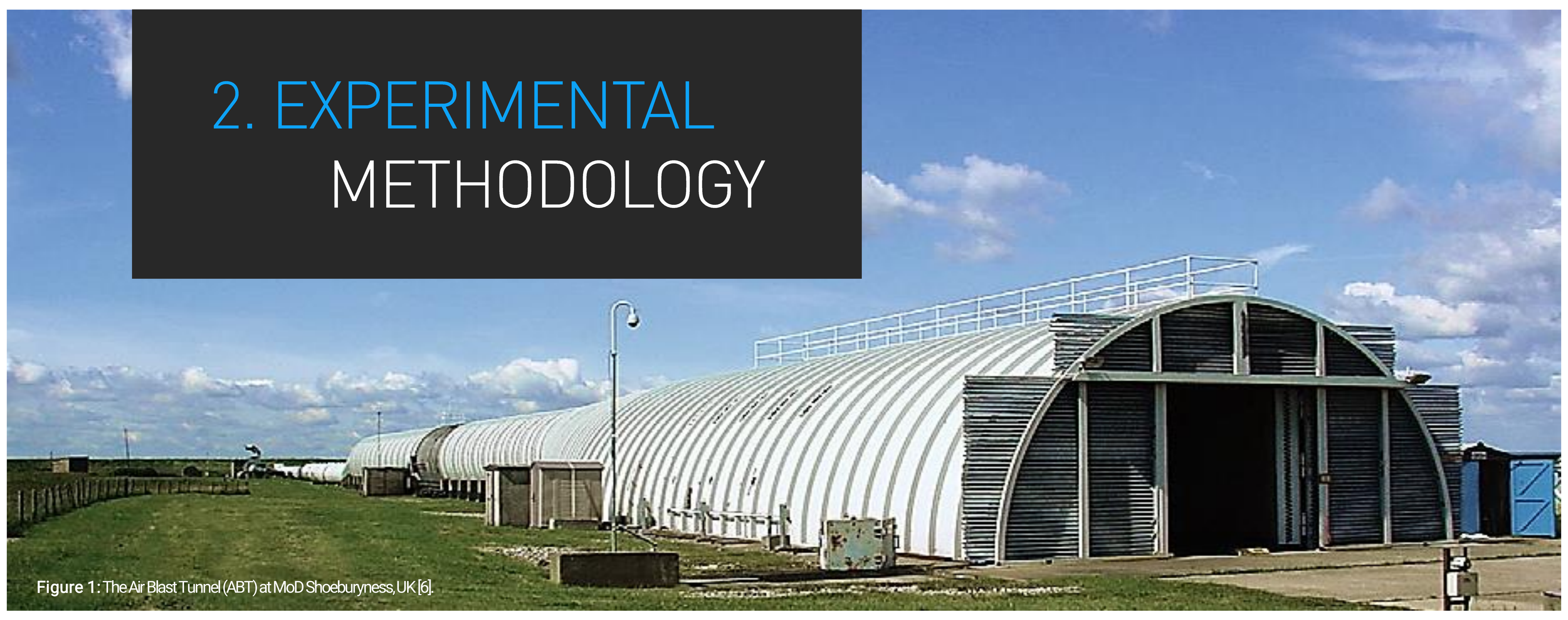
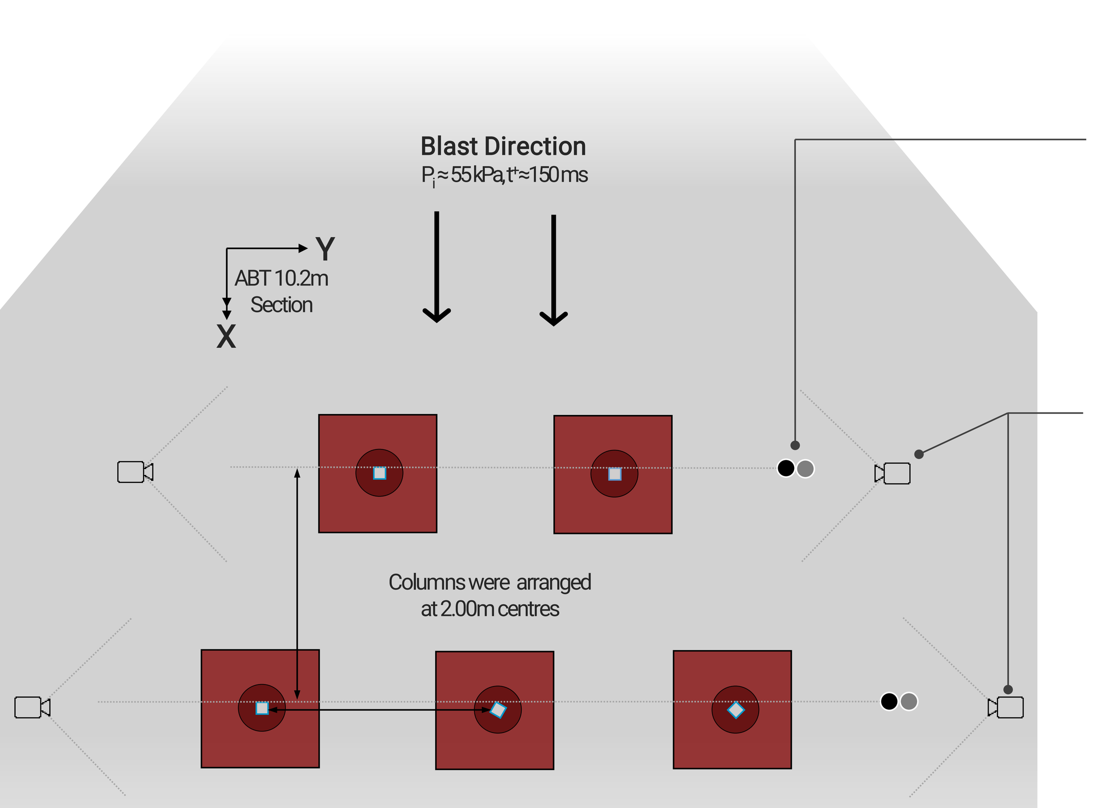


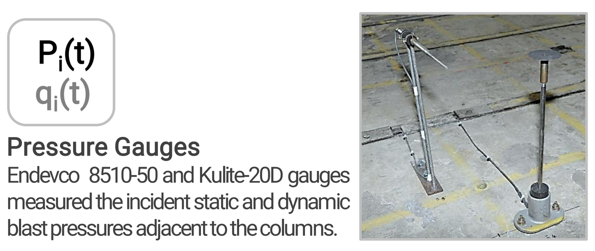
Figure 1: The Air Blast Tunnel (ABT) at MoD Shoeburyness, UK [6].

The Air Blast Tunnel (ABT)

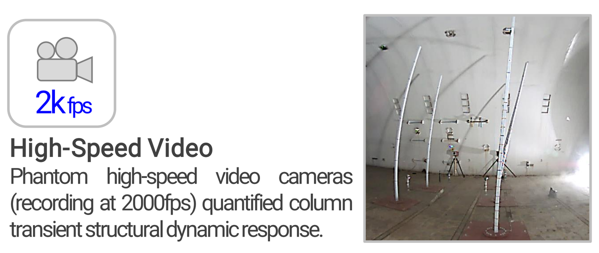
Long-duration blast waves were generated within the Air Blast Tunnel (ABT) facility at MOD Shoeburyness, UK (Figure 1). Constructed in 1964, the ABT is the only UK facility capable of generating long-duration blasts, allowing specialist analysis of the loading effects and response of structures. A consistent blast environment was sought for each trial comprising peak overpressures of P_i≈55kPa and positive phase durations of t^+≈150ms.



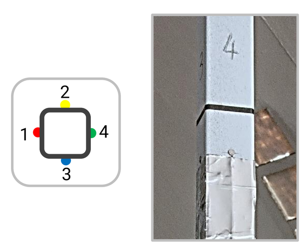
Laser Topology
High-fidelity laser topology quantified column permanent (plastic) deformation as a function of section orientation.



Pressure Gauges
Endevco 8510-50 and Kulite-20D gauges measured the incident static and dynamic blast pressures adjacent to the columns.



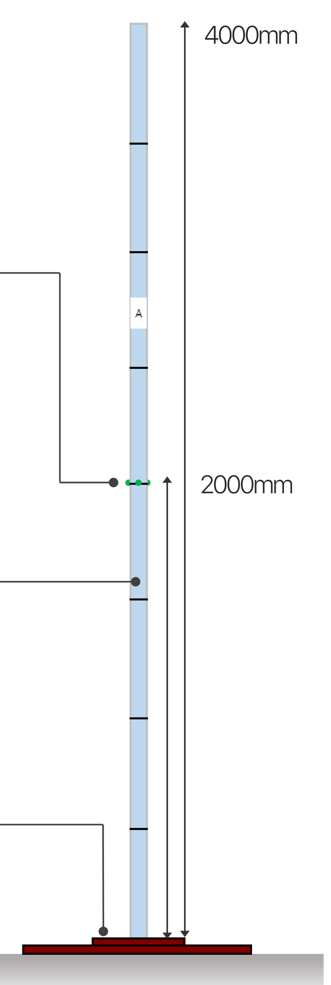
High-Speed Video
Phantom high-speed video cameras (recording at 2000fps) quantified column transient structural dynamic response.



Surface Pressure Gauges
Columns were instrumented with Endevco 8510-50 pressure transducers to measure blast interaction and transient pressures exerted on respective column surfaces. Importantly, this enabled calculating net loading exerted on the columns as a function of section orientation.

Steel SHS Columns
Mild steel (S235) square hollow sections (SHS 50x50x2.0) with total height of 4.0m were configured as cantilevers to generate the largest possible flexural response to the blast loading conditions inside the ABT.

Circular Baseplate
A bespoke circular base plate design provided a fixed boundary condition and allowed different SHS column orientations.



Experimental Setup

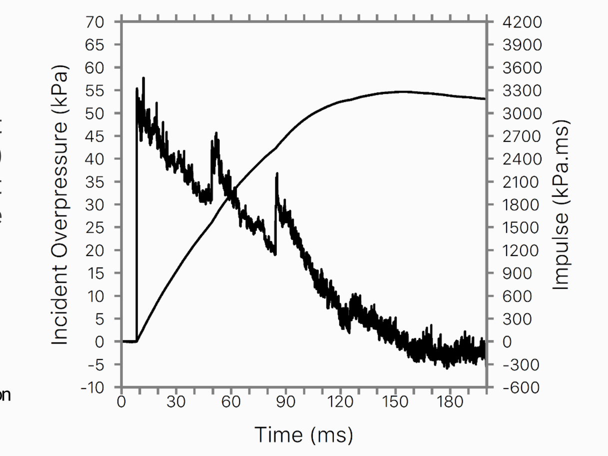
A total of ten mild steel (S235) square hollow section columns (SHS 50x50x2.0) were subjected to long-duration blast loading inside the ABT aligned at orientations of 0, 30 and 45 degrees to the direction of blast propagation. Blast loading, transient dynamic and permanent structural response were measured as a function of the column section orientation to the blast.

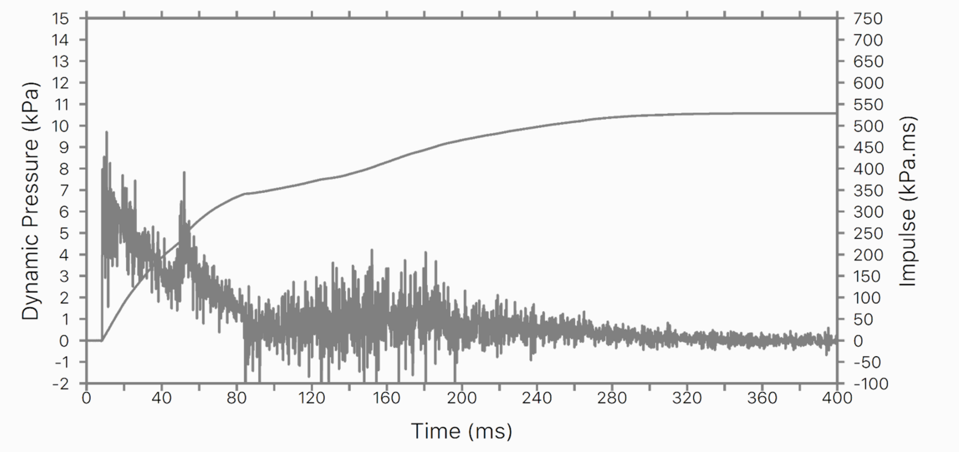
3. EXPERIMENTAL RESULTS & ANALYSIS

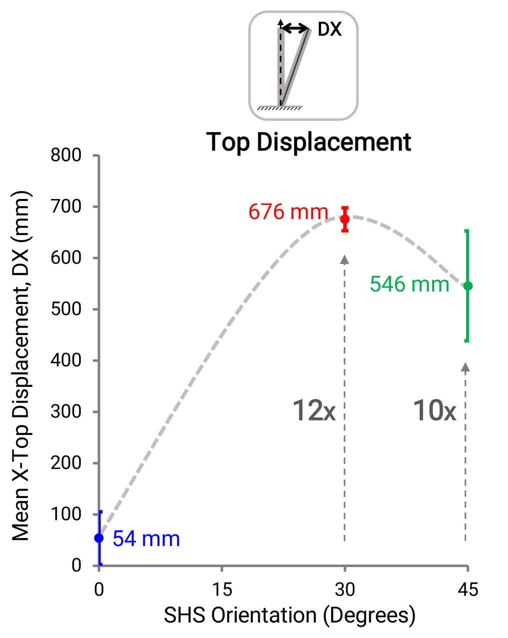
Incident Blast Environment

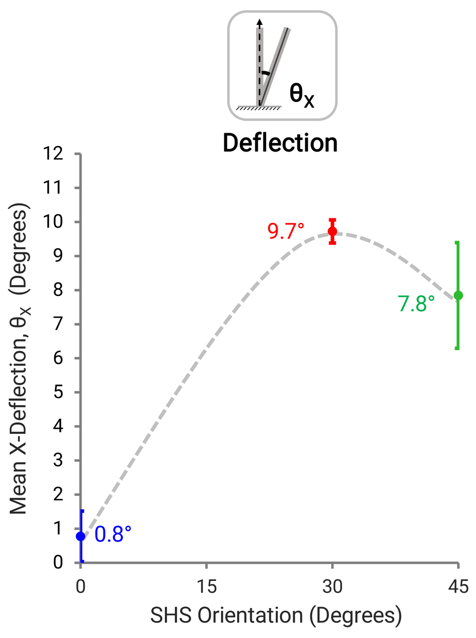
A consistent blast environment (static and dynamic overpressures) was achieved for all trials such that each column was subjected to the same incident blast loading.

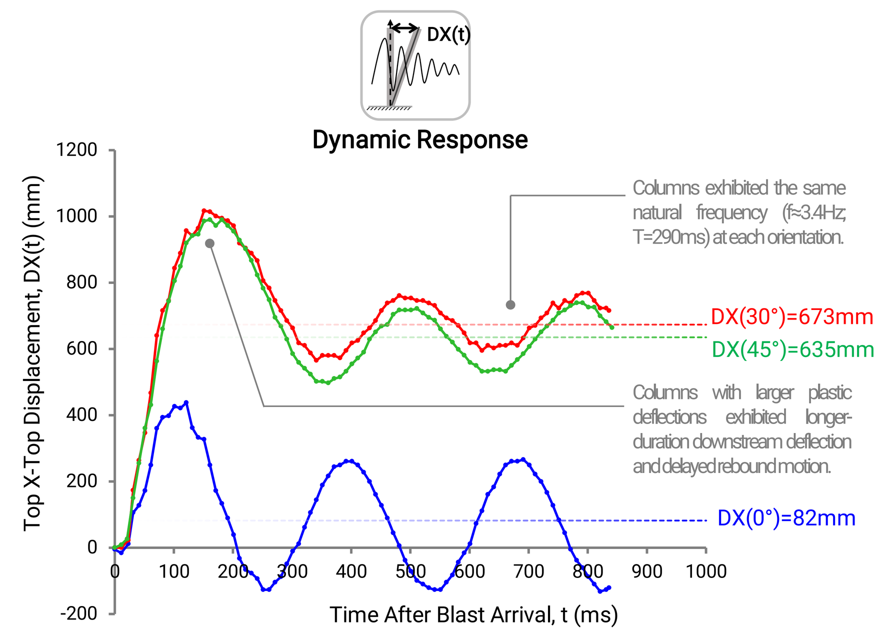
55kPa Peak Overpressure · **150**ms Positive phase duration

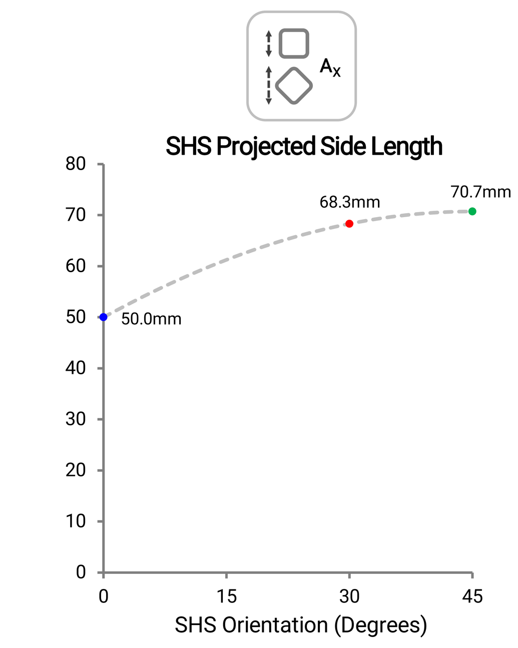


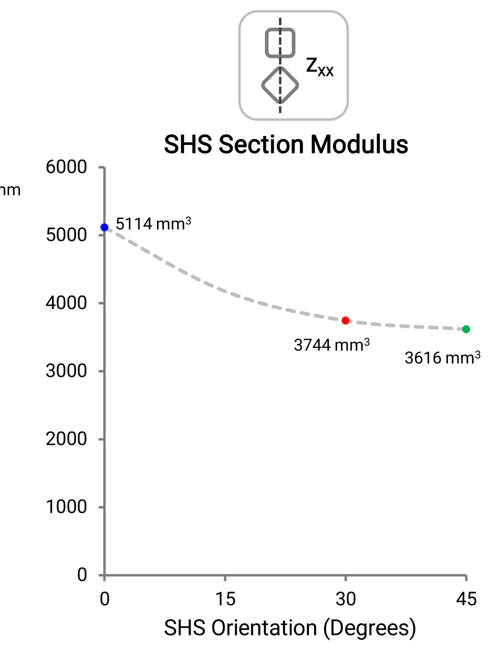












Harmonic Response f_n(θ°)

Columns undergoing larger deflections exhibited modified harmonic behaviour, attributed to plastic hinge formation, including:

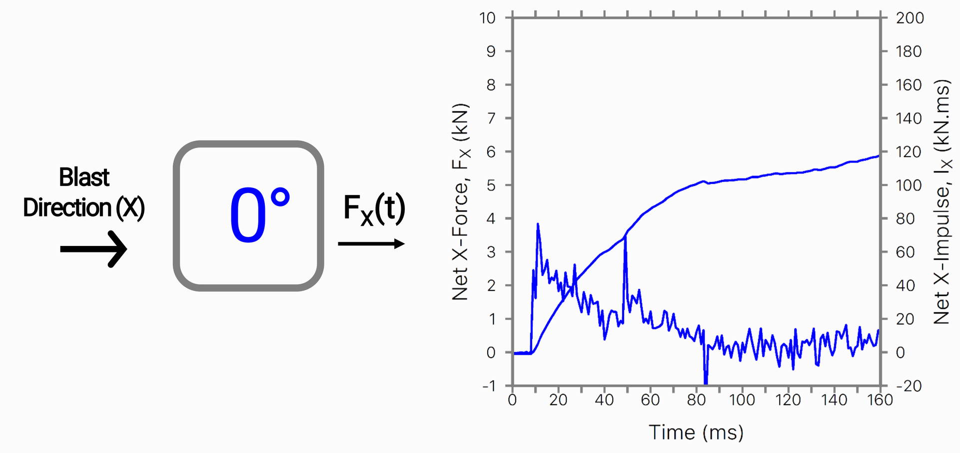
- longer-duration downstream deflection and delayed rebound motion;
- reduced amplitude oscillations, indicating increased structural damping.

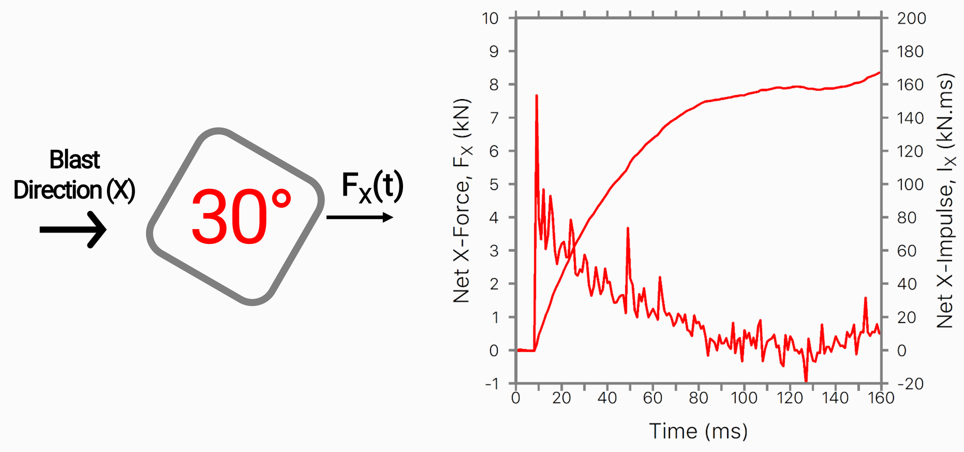
Displacement & Deflection f_n(θ°)

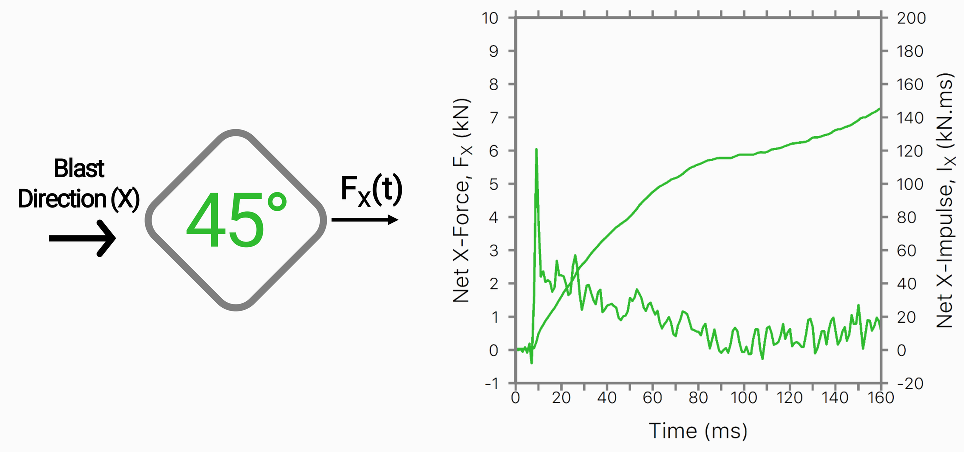
Column top displacement and final deflection varied significantly with SHS orientation to the blast, demonstrating that section orientation is non-trivial.

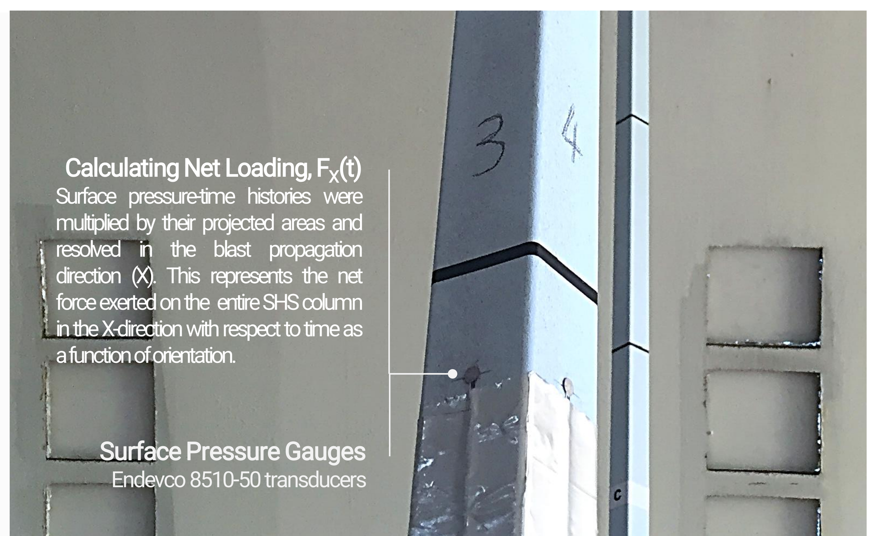
Maximum top displacement and deflection occurred at 30° (≈12x larger than at 0°), followed by 45° and minimal response at the 0° orientation.

45° SHS orientation has the highest projected area and lowest section bending modulus (structural resistance), yet a 30° orientation consistently resulted in larger plastic deflections.



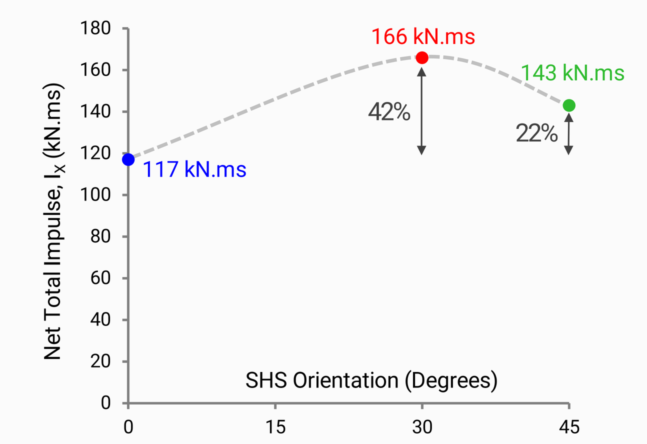






Calculating Net Loading, F_X(t)
Surface pressure-time histories were multiplied by their projected areas and resolved in the blast propagation direction (X). This represents the net force exerted on the entire SHS column in the X-direction with respect to time as a function of orientation.

Surface Pressure Gauges
Endevco 8510-50 transducers



Column Blast Loading f_n(θ°)

Column blast loading demonstrated clear variation with SHS orientation, influenced by both drag aerodynamics and projected area to the blast.

Highest net loading occurred at 30° despite the 45° orientation having the largest projected area. Importantly, this demonstrates that blast interaction and transient aerodynamics require accurate characterisation or suitable drag coefficients with provision for different section orientations.

4. CONCLUSIONS & IMPACT

- Column section orientation greatly influences net blast loading and structural response due to varying projected area, section aerodynamics and structural flexural resistance (section modulus).
- Largest SHS structural response and plastic deflection occurred at a 30° orientation despite 45° having the largest projected area and lowest section modulus; this demonstrates that aerodynamic drag loading as a function of section orientation is non-trivial and requires accurate characterisation.
- Results provide reason to question the accuracy of current simplified blast design approaches and for engineers and designers to consider the effects of column section orientation where relevant.

References

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