The influence of pretension on reinforced concrete beams subjected to fuel tanker explosions.

Joel Smith[1], James Bache[2], Jessica Klimenko[2], and Ben Smith[1]

[1] Arup Australia Pty Ltd, Sky Park, One Melbourne Quarter, 699 Collins St, Docklands, VIC, 3008, Australia;
[2] Arup Australia Pty Ltd, Level 5, Barrack Place, 151 Clarence St, Sydney, NSW, 2000, Australia.

Abstract

Pretension in reinforced concrete beams is commonly used within the construction industry to provide sufficient precompression to the tension face of an element, such that static dead and live loads develop low or no tension stress within the concrete components of the element. While this is advantageous for conventional structural design, allowing the element to carry more load over longer spans, beam elements subjected to significant uplift loading, such as those experienced during an accidental explosion, can develop additional tensile stresses on the element's top surface.

This paper presents an investigation into the use of pretensioned beam elements to construct a pedestrian structure over an existing dangerous goods transportation route. Utilising LS-DYNA, the impact of a fuel tanker explosion occurring underneath on the integrity of the structure and the potential risk to life safety are interrogated.

Pretensioned beam elements have a distinct construction sequence that affects the internal stress state prior to the application of accidental blast loads. To capture this, the pretension, placement, and design load applications occur in distinctly separate phases.

Computational Fluid Dynamics (CFD) analysis with Viper::Blast was completed on the beam mesh to calculate the blast loads over the span of the element, while also considering reflected surfaces from nearby structures and the roadway underneath the fuel tanker.

Post blast loading and rebound phases in the model have been interrogated against the typical failure modes identified for a reinforced concrete beam element, such as flexure cracking, compressive crushing of concrete and yielding of reinforcement components. Finally, a sensitivity study was conducted on under pretensioning the element relative to the structural engineering design. This was intended to better understand the potential failure modes under uplift blast loading and potentially find a better balance between the structural design requirements and resilience under accidental blast loads.

1 Introduction

Pretension in reinforced concrete beams is commonly used within the construction industry to provide sufficient precompression to the tension face an element, such that static dead and live loads develop low or no tension stress within the concrete components of the element. While this is advantageous for conventional structural design, allowing the element to carry more load over longer spans, beam elements subjected to significant uplift loading, such as those experienced during an accidental explosion, can develop additional tensile stresses on the element's top surface.

This paper presents an investigation into the use of pretensioned beam elements to construct a pedestrian structure over an existing dangerous goods transportation route. Utilising LS-DYNA, the impact of a fuel tanker explosion occurring underneath on the integrity of the structure and the potential risk to life safety are interrogated.

2 Overpressure Derivation

Three blast scenarios are considered for the assessment of the pre-tension beam; a tanker blast explosion, a Boiling Liquid Expanding Vapour Explosion (BLEVE) and a confined Vapour Cloud Explosion (VCE).

The tanker blast scenario is expected to have higher peak over-pressures directly over the hazard while the BLEVE and VCE would have a lower peak but spread more evenly across the length of the pretensioned beam due to the expansion of the dangerous goods. This is represented in Fig.1: with the tanker blast and BLEVE scenarios expected to govern structural response, however this paper focus on the tanker blast scenario only.

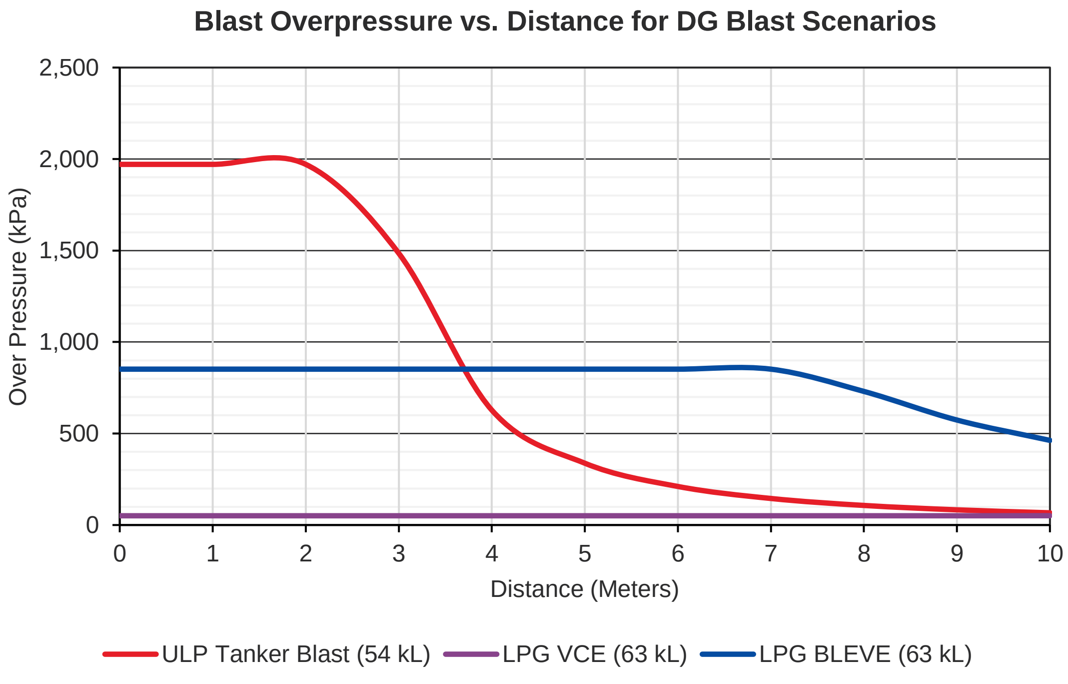


Fig.1: Anticipated Explosive Overpressure vs Distance for the 3 Identified DG Explosive Scenarios

2.1 Tanker Blast Explosion

The tanker blast explosion is an extremely confined explosion which occurs when the residual vapours in an empty tanker are in the necessary stoichiometric ratio to oxygen and exposed to an ignition source. This scenario was converted into a TNT equivalence of 45kg with a 12m long cylindrical charge as shown by Fig.2:. Computational Fluid Dynamics (CFD) was conducted using Viper::Blast, this allowed the 3D geometry of the pre-tensioned planks to be considered and capture any confinement effects caused by surrounding elements including the road surface.

Pressure gauges are placed down the length of the pretensioned beam to record the pressure-time history for further use in structural analysis.

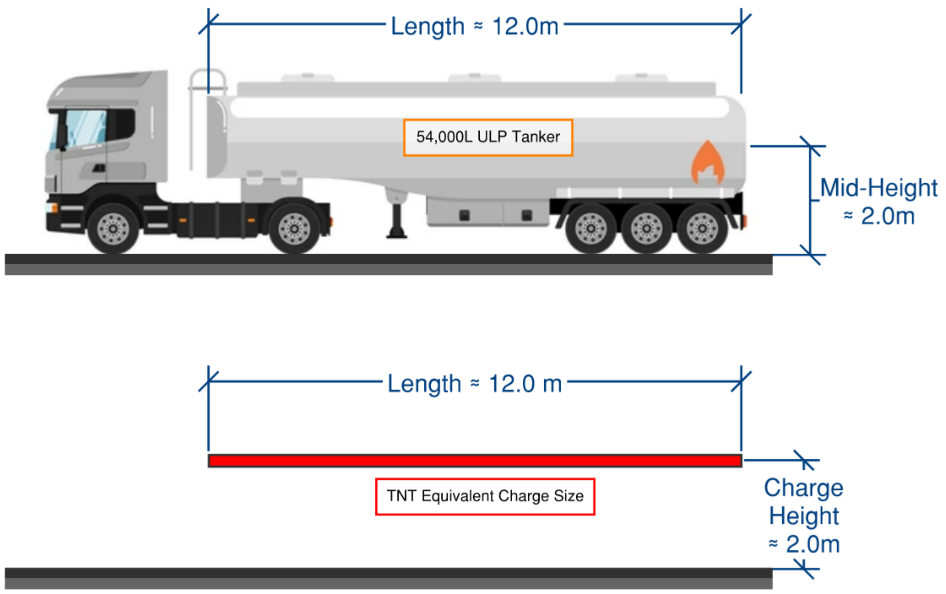


Fig.2: Tanker Parameters to Equivalent TNT Charge Parameters

3 Model Setup

3.1 Geometry

The pretensioned beam model used a combination of solid (4,033,750), shell (70,000) and beam (227,150) elements. A breakdown by part, including element formulation is shown in Table 1:

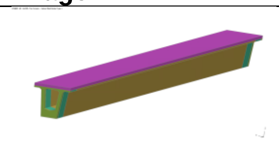
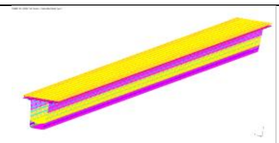
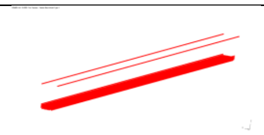
Part	Element Type	ELFORM	Image
Concrete	SOLID	1	
Reinforcement	BEAM	1	
Tension Cables	BEAM	6	
End Supports	SHELL	2	

Table 1: Parts and Element Types

3.2 Concrete Material

The model has utilised the material model **`*MAT_084: WINFRITH CONCRETE`** for the concrete, to allow the formation and size of cracks to be captured. The inputs to the material model were generated using cube crush simulations and compared against stress strain curves generated using parameters from Eurocode 2 (EN 1992-1-1:2004) Table 3.1, shown below in Fig.3:.

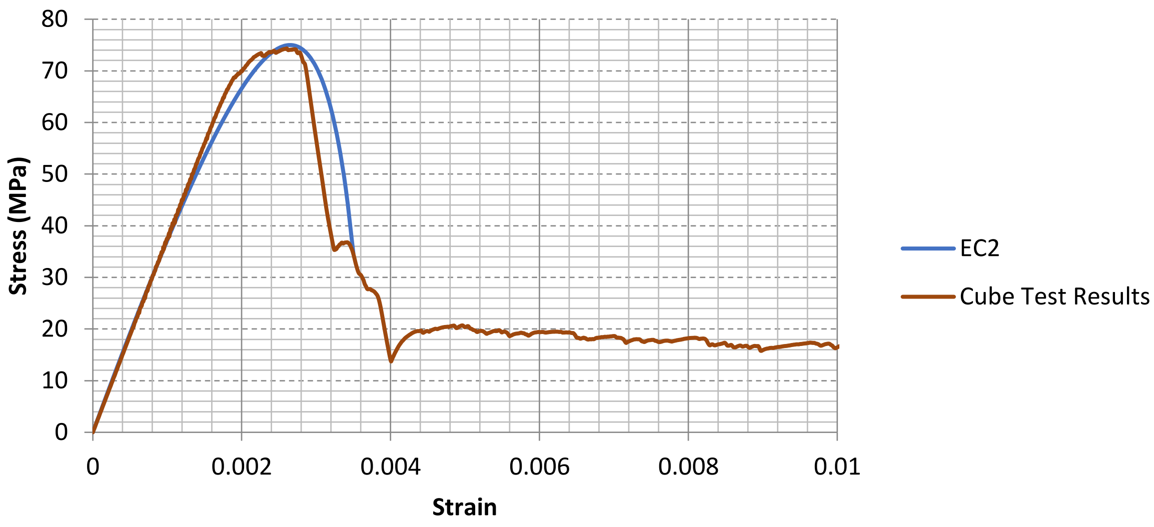


Fig.3: Stress-Strain Curve from Material Characterisation

3.3 Boundary Conditions

The pretension beam spanned approximately 33m between supports. The supports themselves were modelled as rigid shell elements for simplicity. The contact between the beam and supports was modelled with two sperate instances of **`*AUTOMATIC_SURFACE_TO_SURFACE`**, one with zero contact friction (to allow smooth pretensioning) and the other with a typical concrete-concrete friction value of 0.5 for both dynamic and static. The two contacts had equivalent death and birth times to allow the transition from ‘off-site’ pretensioning to installation ‘on-site’. The pretensioned beam ends were split into separate parts to create more efficient contacts during the simulation and save run time.

3.4 Pretension

The pretension cables were modelled as ELFORM 6 (Discrete beam/cable) Beams give a cross-sectional area value to match the 15.2mm diameter specified. The pretension was implemented on the material card where **`*MAT_071: CABLE_DISCRETE_BEAM`** was used with a pretension per cable of 158.3kN.

The concrete stress block under the pretension state was checked without the topping slab to ensure the model was predicting the correct initial stress’. The results of the hand calculations and comparisons to Maximum Principal Stress and Minimum Principal Stress results from the simulation, this is shown in Fig.4:.

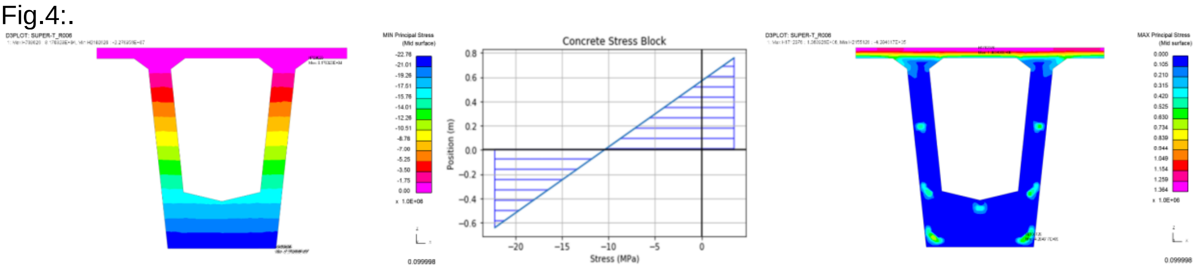


Fig.4: (a) Minimum Principal Stress Results, (b) Expected Concrete Stress Block, (c) Maximum Principal Stress

To mitigate local effects at the free edges caused by the pretension of the beam a small section of solid elements has been modelled with **`*MAT_001: ELASTIC`**. These fully elastic elements were kept sufficiently far from the expected damage locations to minimise their effects on the final results.

3.5 Static Loads

The additional static loading was applied as **`*LOAD_SEGMENT_SET`** to the top surface of the pretensioned beam, in additional to gravity via **`*LOAD_BODY`**. The application of the static load was staggered after the pretension and gravity was applied to best captured the true construction and loading sequence.

As is typical with pretensioned beams the deflection is neutral once the static loads are applied, this differs from standard beams which would have a tension (bottom) and compression (top) face under the static loads.

3.6 Blast Loads

The blast loads derived from gauge points in the Viper::Blast CFD model were translated into **`*DEFINE_CURVE`** format and applied as **`*LOAD_SEGMENT_SET`** to the bottom face of the beam. Although Viper::Blast does have the capability to calculate the pressure-time history for individual segments in an LS-DYNA model this capability was not used due to the large model size.

Instead, the loads were applied uniformly for discrete segments, with smaller segments closer to the charge.

4 Considered Failure Modes

To assess the performance of the pretensioned beam, potential failure modes with potential to result in further structural collapse were examined and checking methodologies were established before running the analysis. The following eight critical failure modes and the loading phase in which they occur are identified in Table 2:.

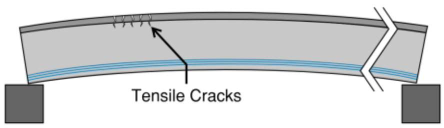
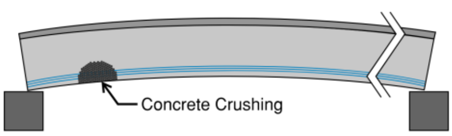
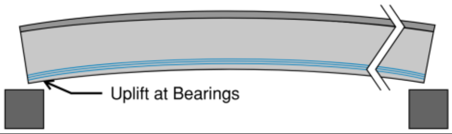
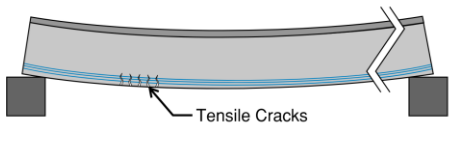
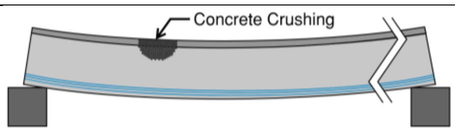
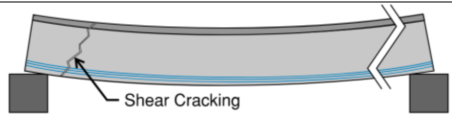
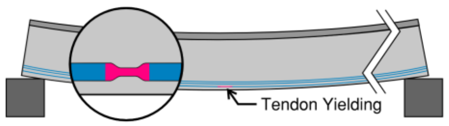
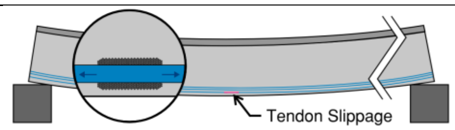
Phase	**Failure Mode**	**Indicative Diagram**	**Potential Failure Mechanism**
Initial Blast (Uplift Phase)	Flexure: Tension		Tensile cracking of the topping slab propagates, reducing capacity. Tensile cracking in the top of the plank itself leads to a loss in element capacity
	Flexure: Compression		Crushing of the topping slab upon rebound leads to loss of section capacity. Concrete bond to the tendons is damaged via localised crushing
	Plank Uplift		Gravity loads are overcome, causing the plank to become detached from its bearings.
Rebound Phase	Flexure: Tension		Tensile capacity of concrete is exceeded causing cracks to propagate through section. Tensile capacity of tendons is exceeded causing yielding and leading to concrete cracking
	Flexure: Compression		Crushing of the topping slab upon rebound leads to loss of section capacity. Crushing at the top of the plank upon rebound leads to loss of capacity
	Diagonal Shear		Shear cracks occur near supports in rebound response. Propagation of cracks reduces the elements capacity
Both Phases	Tendon Yielding		Overstressed tendon yields, reducing the prestress in the element, leading to collapse
	Tendon Slippage		Bond between tendon and concrete slips, losing prestress in the element

Table 2: Potential Pretensioned Beam Failure Modes

5 Results

5.1.1 Uplift Phase

During the initial uplift phase, the Maximum Principal Stress on the top of the element (Fig.5:) remains below the tensile capacity of the concrete (4.83MPa), This failure mode is a particular concern for pretensioned elements as the top face of the beam carries more tension than a standard beam element. Some tensile cracking in the topping slab occurs near the supports but these cracks do not extend into the main structural beam.

End sections of the element show high stress; however, these are induced in the pre-loading phase and are caused by the model boundary conditions. These stresses are not likely to occur in the real element and are thus not considered a concern within this assessment.

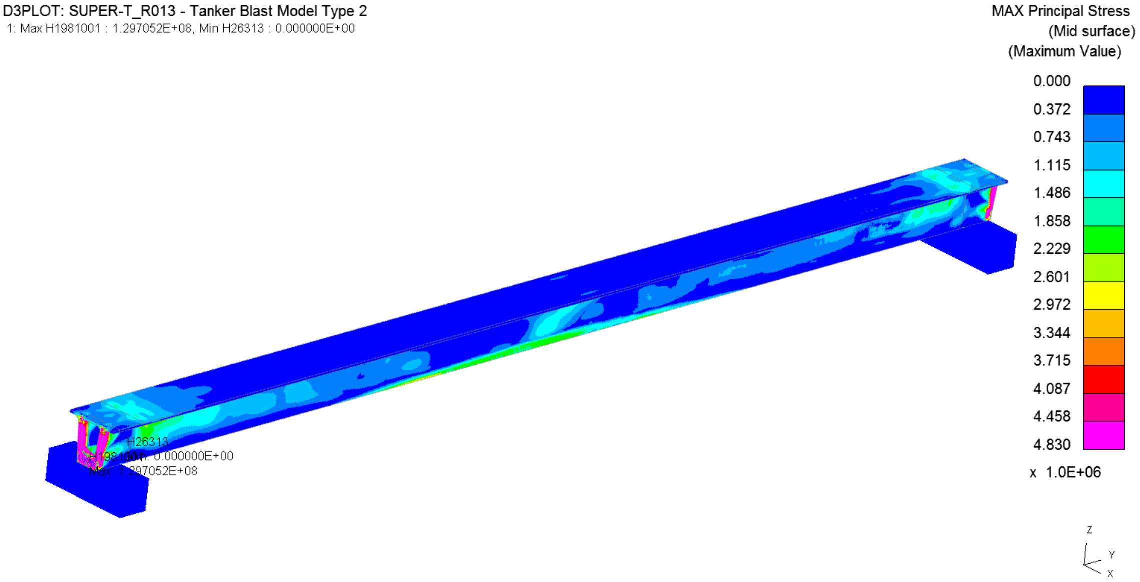


Fig.5: Tanker Blast Model Max Principal Stress Envelope Plot, ISO Top View, Topping Slab Hidden [0-4.83MPa]

The underside compression during the uplift phase is also a concern as the pretension sets an initial compression stress on this face, where a typical beam would experience tension, thus increasing the risk of concrete crushing during the initial blast uplift. The Minimum Principal Stresses on the underside (Fig.6:) of the element remain below the compression capacity of the concrete (65MPa), indicating failure in flexural compression due to concrete crushing is unlikely.

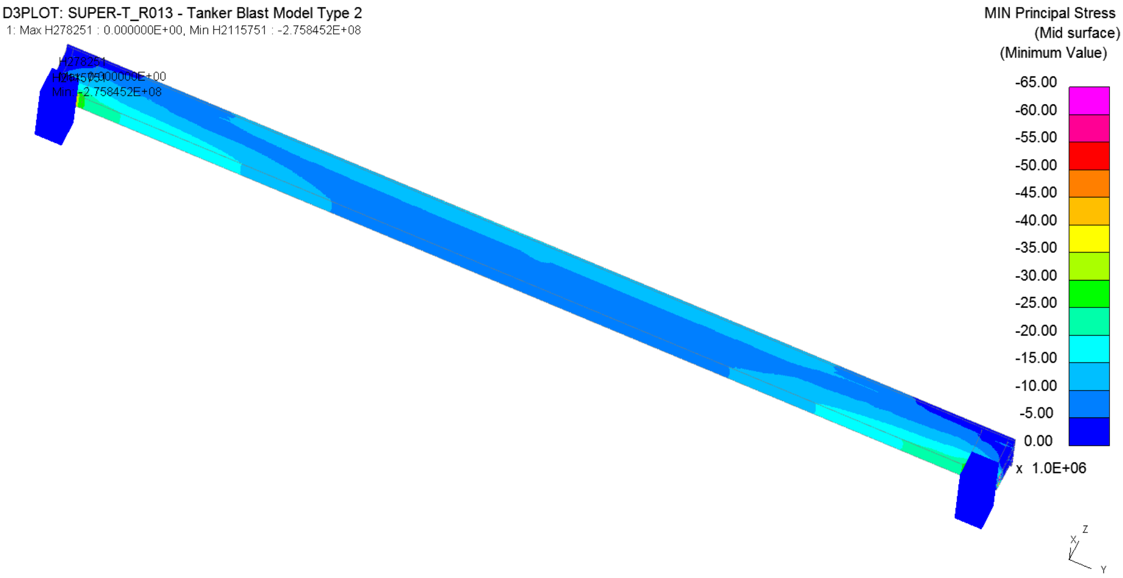


Fig.6: Tanker Blast Model Min Principal Stress Envelope Plot, ISO Bottom View [-65-0MPa]

Fig.7: shows a brief period where the support closest to the explosion experiences 0kN vertical force, indicating the pretension beam comes close to disengaging, though assessed as unlikely to result in collapse. Pretension is not expected to have a measurable effect on the disengagement failure mechanism compared to a typical beam.

Membrane action of the topping slab is not captured by the single pretension beam models, though this mechanism is expected to improve disengagement results.

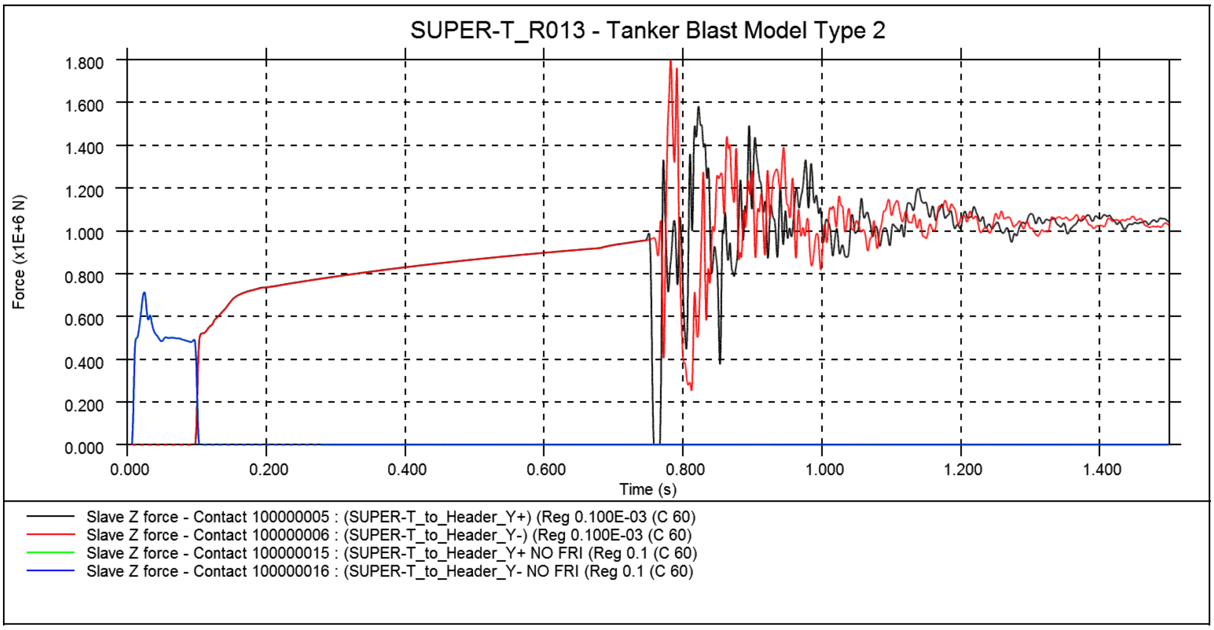


Fig.7: Tanker Blast Model Support Force Plot [0-1.8E6N]

5.1.2 Rebound Phase

During the rebound phase, the beam pretension is expected to provide a positive effect, as the top face would typically enter a compression phase and the pretension minimises this effect. Minimum Principal Stress (Fig.14) values on the top of the element remain well below the concrete compressive stress.

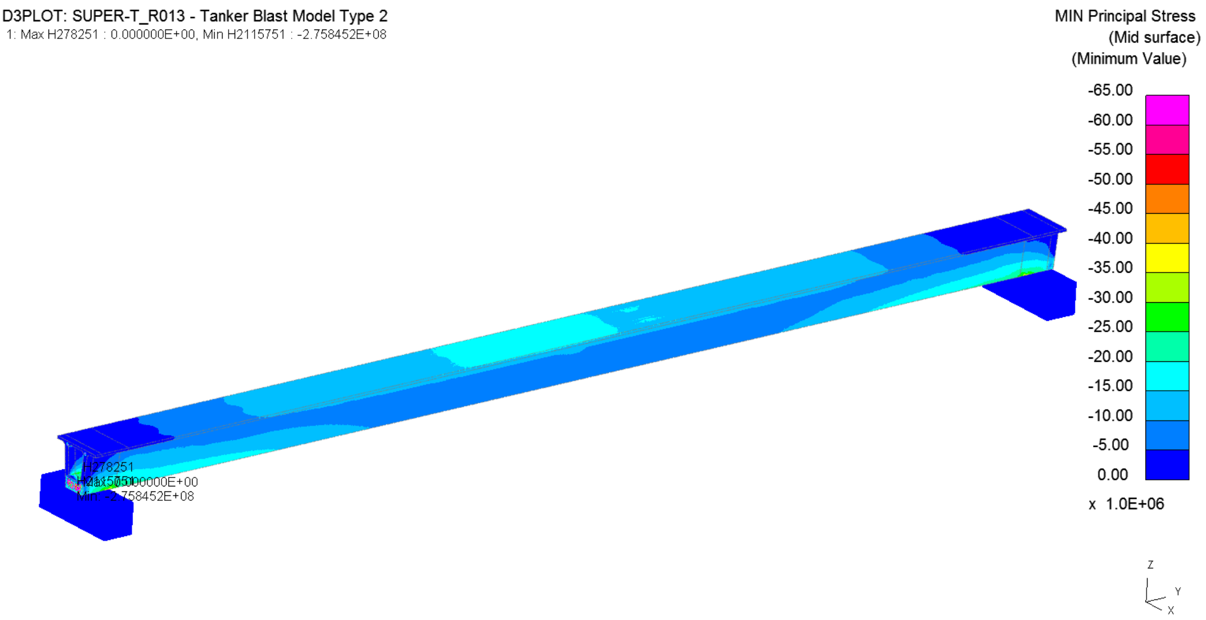


Fig.8: Tanker Blast Model Min Principal Stress Envelope Plot, ISO Top View, Topping Slab Hidden [-65-0MPa]

The Maximum Principal Stress (Fig.15) on the bottom of the element remains below the tensile capacity of the concrete (4.83MPa), once again the pretensioning of the model produces a positive effect for this mode as the face begins in a net compression. Cracking occurs on the bottom face of the element as shown by Fig.10:, however these cracks remain small and do not propagate far up the element.

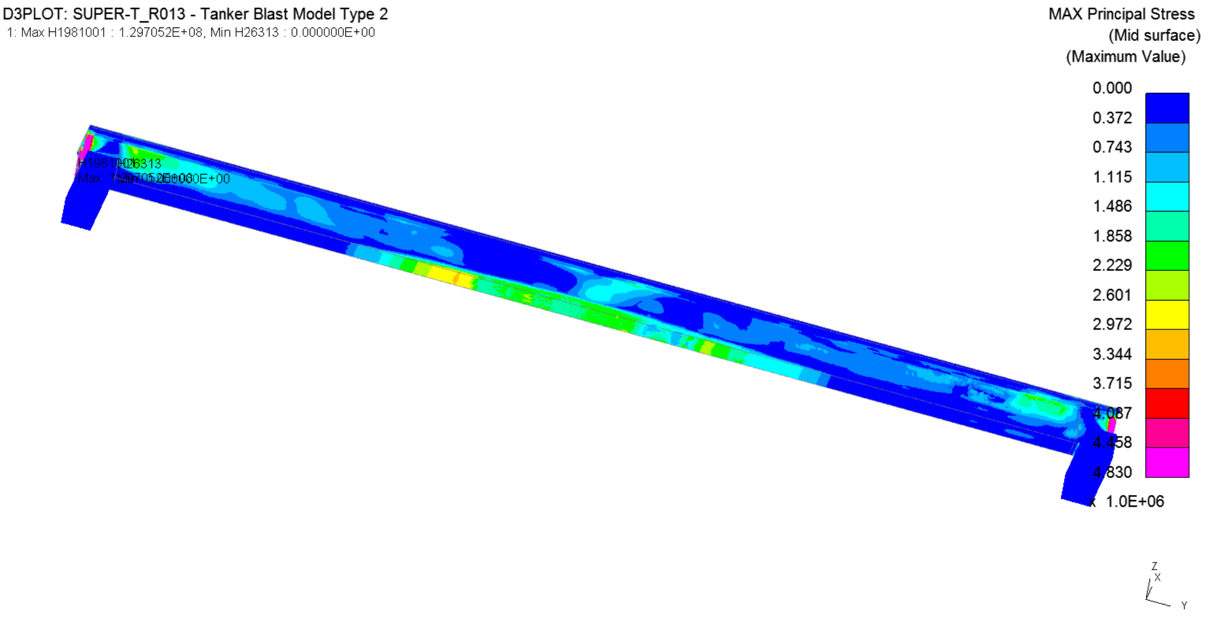


Fig.9: Tanker Blast Max Principal Stress Envelope Plot, ISO Bottom View [0-4.83MPa]

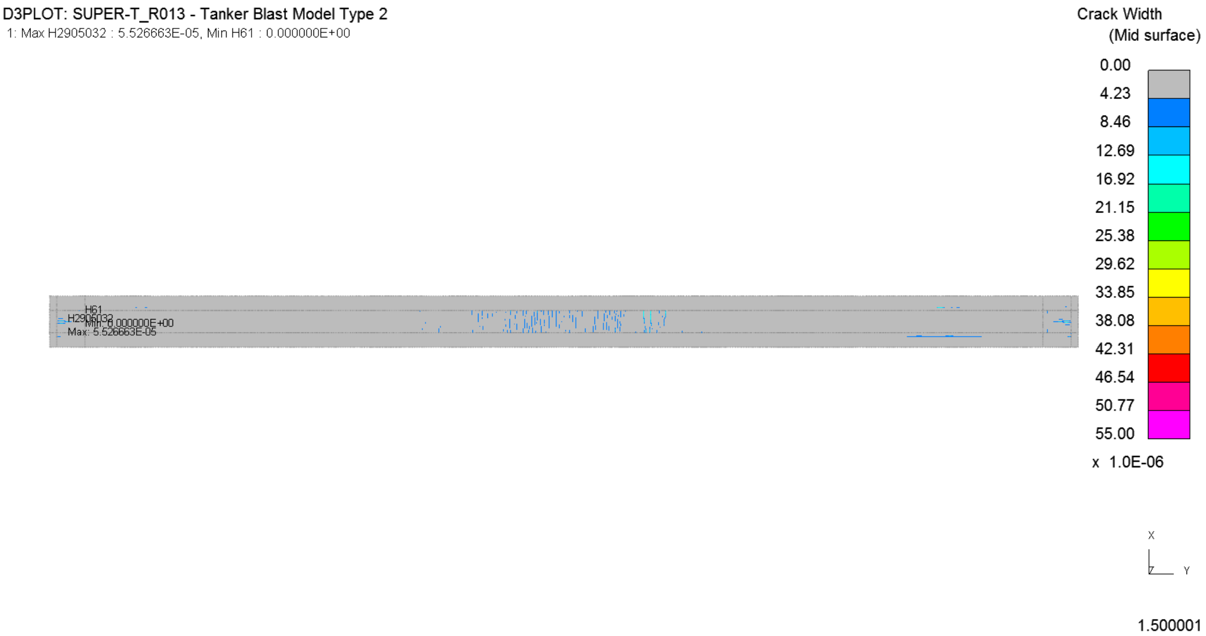


Fig.10: Tanker Blast Model Crack Width Plot, Bottom View [0-55µm] t= 1.5s

Diagonal shear cracks start to form on the inside and outside surface of the element under the rebound response. Fig.11:shows a section down the centre of the element, identifying cracks on the internal face. The shear cracks remain small (~15µm), and as such, can be mitigated through increasing the height of the shear reinforcement throughout the section.

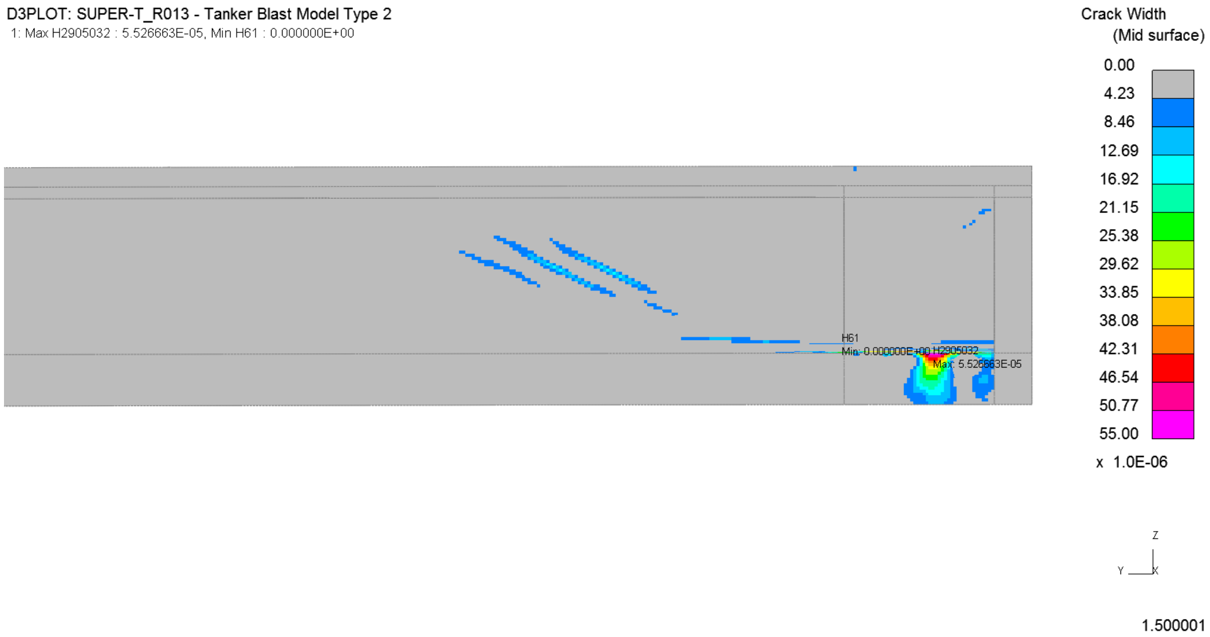


Fig.11: Tanker Blast Crack Width Plot, Section View (End), Topping Slab Shown [0-55µm] t= 1.5s

The rebound phase drives additional tension forces within the pretension tendons. The tendons on the bottom of the element reaching a maximum tension of 169kN, as shown by Fig.12:, a small increase in the static design condition. This increase was checked with additional verification that it would not result in debonding or slipping of the pretension tendons.

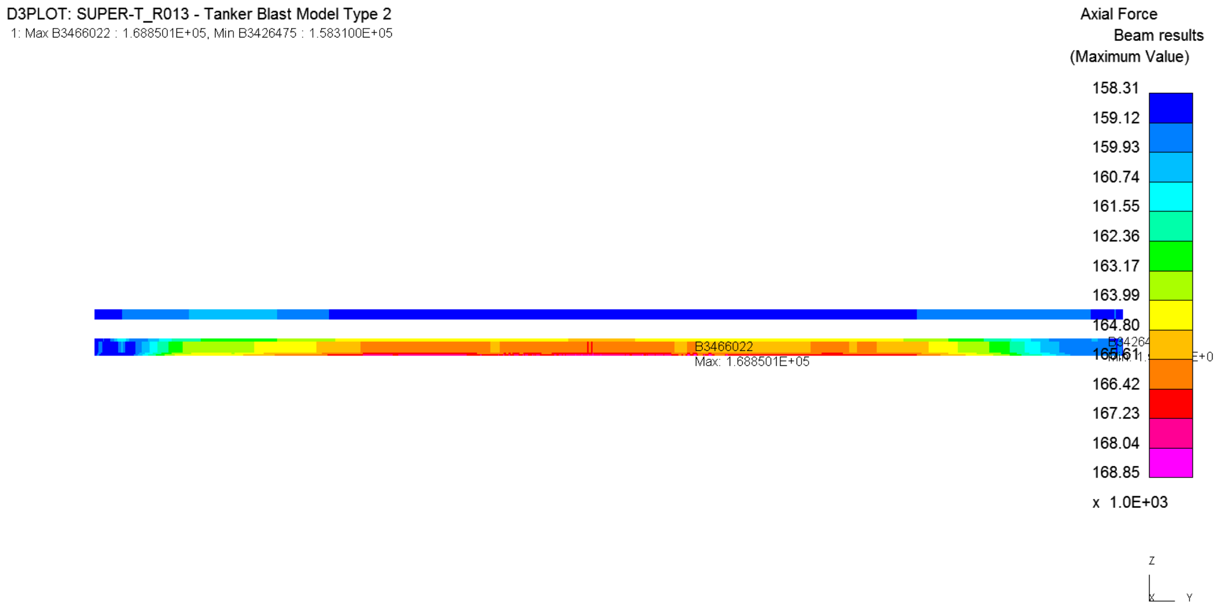


Fig.12: Tanker Blast Model Tendon Axial Force Plot, Side View [158.3-168.85kN]

6 Comparison to no pretension

As discussed in Section 5, the pretension in the beams is expected to have a negative performance effect in the initial uplift loading phase (where the element enters a stress state superposition of preload and applied blast load), and a positive performance effect on the rebound phase (where the element would enter a stress state opposed to the pretension effect).

From Fig.13:the static loading, which creates an initial precompression in the top face of the beam, is not overcome by the tanker blast pressure loads and thus the Maximum Principal Stress does not exceed zero. This is emphasised by the lack of cracking on the top surface in Fig.14: compared to the pretensioned model which showed minor cracks on the top surface near the supports.

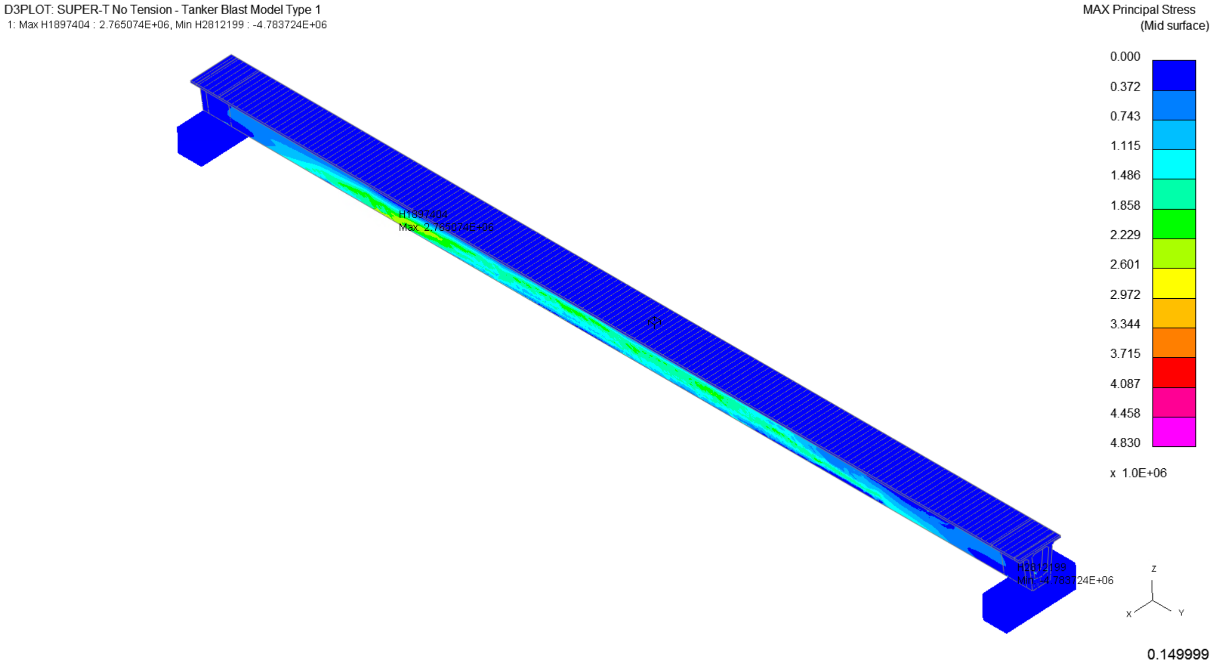


Fig.13: Tanker Blast Max Principal Stress Plot, ISO Top View [0-4.83MPa]

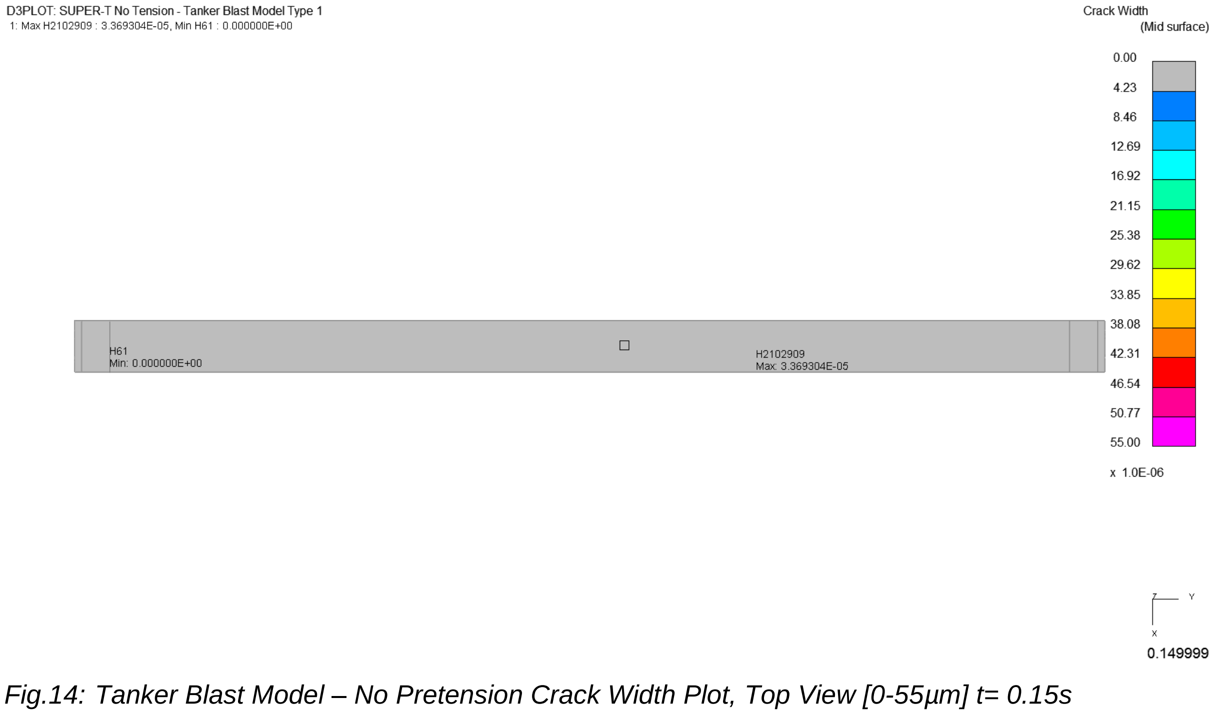


Fig.14: Tanker Blast Model – No Pretension Crack Width Plot, Top View [0-55µm] t= 0.15s

The rebound phase is where the pretension elements do show an increase in performance compared to un-pretensioned. Fig.15: shows extensive cracking compared to Fig.10: with the maximum crack width increasing from 55µm to 0.24mm when no pretension is applied.

Fig.15: Tanker Blast Model – No Pretension Crack Width Plot, Top View [0-55µm] t=0.65s

Overall, the pretension appears to be a positive influence on the beam under the tanker blast loading, however more intense blast loads or significant impulses which may develop more tension in the initial uplift phase may lead to additional tensile cracking on the top surfaces.

7 Summary

This paper has investigated an analysis workflow for the assessment of pretensioned beams subject to accidental blast loads created by a dangerous goods transportation hazard. Initial concerns that the pretension, which creates a more neutral initial stress state compared to traditional beam design, may contribute to additional failure modes when superimposed with blast loads in the initial uplift phase, were not shown to be founded in this scenario.

To understand the true impacts of the pretension, the same beam was modelled without pretension. This analysis showed reduced cracking within the top face, caused by the reduced tension associated with the preload. However, the performance of the underside of the beam, which experiences tension under the static design loads, showed increased cracking which would potentially lead to failure of the element if the cracks continued to open under the static loading.

8 Literature

References should be given in the last paragraph of your manuscript. Please use following scheme:

[1] LS-DYNA KEYWORD USER'S MANUAL VOLUME I, LIVERMORE SOFTWARE TECHNOLOGY (LST), r:13109, 2020

[2] LS-DYNA KEYWORD USER'S MANUAL VOLUME II, LIVERMORE SOFTWARE TECHNOLOGY (LST), r:13109, 2020

[3] Viper::Blast User Manual and Examples for Version 1.20.0, Stirling Simulation Services Limited, Issue 1.0, 2021

[4] Methods for vapour cloud explosion blast modelling, A.C. van den Berg, A. Lannoy, Journal of Hazardous Materials, Volume 34, Issue 2, 1993, Pages 151-171,