Assessment of Vent Pipework Structural Support Response to Internal Explosion

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Vent systems are a key safety function in many processing environments and particularly in relation to the provision of blowdown following detection of an accidental process release. When considering internal explosion events, typically the main focus of vent system design is with regards to the potential for pipework rupture, something which can be largely engineered-out by cautious selection of components and appropriate assembly techniques. A lesser consideration is with regards to how an intact vent system responds positionally during an internal explosion event and the hazard associated with sections of the vent system pipework breaking free from their structural supports and being displaced. This paper summarises an approach taken to assess vent system pipework structural support response to an internal explosion to determine the potential for movement of the pipework and the associated hazard potential.

The assessment was undertaken for the vent system of an offshore gas platform in the UK sector of the North Sea. For the purposes of the analysis the vent system was limited to the section of pipework between the knock-out drum and the vent tip.

The approach consisted of two distinct phases: firstly, computational fluid dynamics (CFD) modelling of internal explosions within the vent system to quantity the overpressure loading on the pipework; and secondly, finite element analysis (FEA) modelling of the structural response of the vent system structural supports to determine the potential for failure of the supports which could ultimately enable displacement of the pipework.

The internal explosion modelling was undertaken using FLACS to predict overpressures and ultimately the forces along the internal pipe walls and in particular at the bends between the pipe sections. The results were then used to calculate a time history of net out-of-balance forces on each section of vent pipework which could be taken as an input to the FEA structural response modelling.

Solidworks simulations were undertaken to measure the stresses on the structural support components throughout the duration of the explosion. The results were monitored with respect to the material design tolerances to ultimately determine the potential for component failure that could lead to pipework displacement.

Key Words: Vent, Explosion, Structural Response, CFD, FEA

Introduction

Vent systems are a key safety function in many processing environments [4] and particularly in relation to the provision of blowdown following detection of an accidental process release. When considering internal explosion events, typically the main focus of vent system design is with regards to the potential for pipework rupture, something which can be largely engineered-out by cautious selection of components and appropriate assembly techniques. A lesser consideration is with regards to how an intact vent system responds positionally during an internal explosion event and the hazard associated with sections of the vent system pipework breaking free from their structural supports and being displaced.

This paper summarises an approach taken to assess vent system pipework structural support response to an internal explosion to determine the potential for movement of the pipework and the associated hazard potential. The assessment was undertaken for the vent system of an offshore gas platform in the UK sector of the North Sea and prompted by an operator's need to justify to the regulator the use of a vent system without continuous purging as part of the safety case submission process.

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Vent System

For the purposes of the analysis the vent system was limited to the section of pipework between the knock-out drum and the vent tip. The vent pipework was rated to 19.6 barg (A3 pipework [3]) and had been tested to 29.4 barg. It was understood that all associated fittings (e.g. elbows, instrumentation connections, flanges etc.) were similarly rated. Downstream of the vessel the pipework consisted of 11 sections of piping separated by 10 bends mostly of 90° and three instruments/connection points. The pipework was primarily of 8-inch diameter but included a section of 10-inch diameter. This pipework was supported by a total of 11 structural supports, 5 of which were located within the vertical vent stack, with the remainder spaced along the mainly horizontal pipework upstream of the stack. The arrangement is as shown in Figure 1.

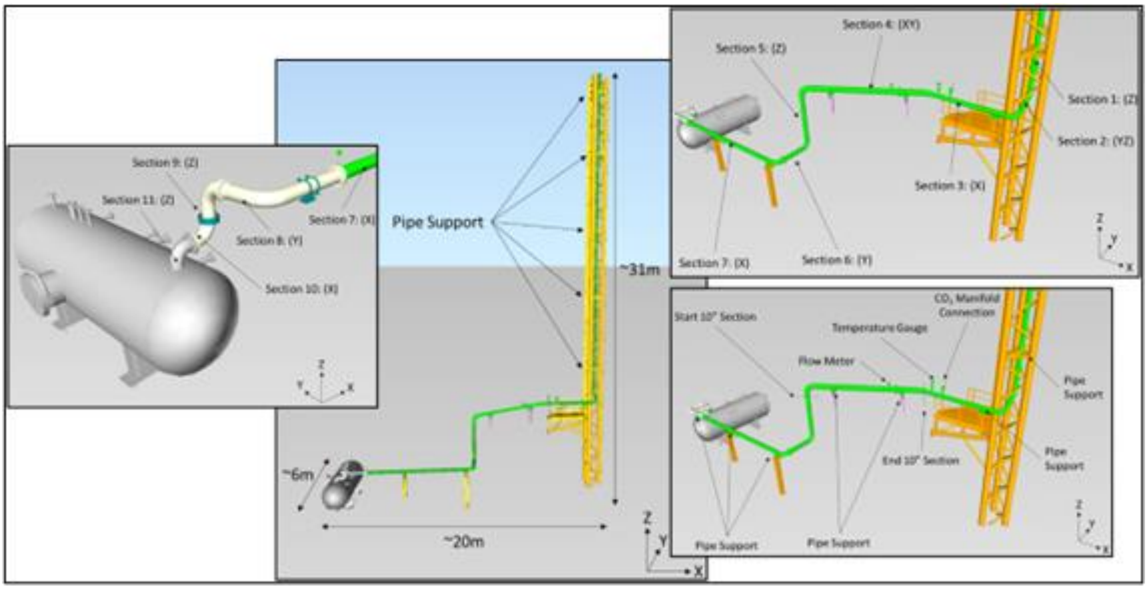

Figure 1: Marked-up images of the vent system: Close up view of knock-out drum (Left); Entire modelled vent system (Centre); Main vent system pipework (Top Right); Locations of pipe supports and instrumentation (Bottom Right)

Explosion Modelling

Objectives

The aim of the explosion modelling was to measure static overpressures, and thereby forces, along the internal surfaces of the vent pipework during explosion events.

3D Model and Gridding

A 3D model of the vent system from the vessel to the vent tip was developed in FLACS v20.1 [2]. FLACS is the preeminent CFD explosion tool used in the oil and gas industry, and, whilst appropriate for this type of modelling, it presents some limitations which needed to be addressed in order to develop a suitable 3D model.

In FLACS, the gridded region corresponds to all space between the minimum and maximum extents in X, Y, and Z of the simulation domain, irrespective of whether those cells fall inside or outside of the region in which the modelling is of interest. Consequently, a long thin piping system may constitute a relatively small internal volume but due to the various bends it may sit within an overall 3D region that is huge by comparison, with the vast majority of cells external to the region of interest. According to FLACS guidelines [2], a minimum of 5 grid cells are required across the flow field (i.e. the pipe internal diameter) in order to adequately model flame front propagation. For an 8-inch diameter pipe this implies cells of the order ~0.04m are required. The simplest representation of the 3D region in which the vent system is located (~20m x ~6m x ~31m) would equate to ~58 million cells which is beyond the practical limits of modelling.

In order to reduce the number of excess grid cells it was necessary to minimise the 3D space required by the vent system. In practice this meant developing an arrangement that appeared to be almost flat in profile by reorientating the bends. Whilst this meant a departure from the actual vent system arrangement in appearance, all pipe section lengths, the number of bends, and their relative positions remained unchanged. The forces exerted at the bends will be dominated by the force from the explosion overpressure and so any inaccuracies in gravitational forces were expected to be insignificant by comparison. Once the forces had been calculated the force directionality was reorientated with respect to the actual vent system arrangement to ensure correct application in the subsequent structural analysis. The arrangement was as shown in Figure 2.

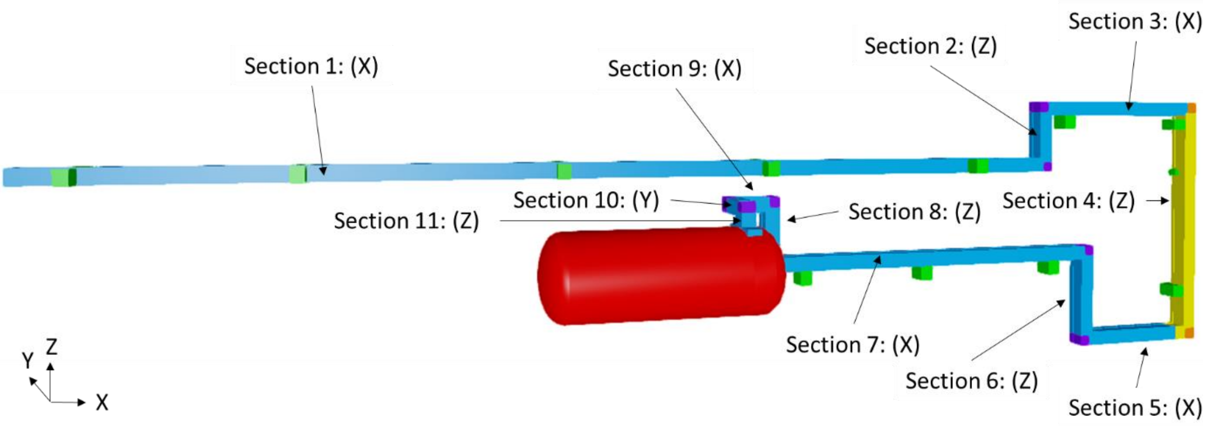

Figure 2: Illustration of FLACS 3D model of vent system arrangement: 8-inch piping (Blue); 10-inch piping (Yellow); Approximate structural support locations (Large Green Blocks); Flow Meter (Small Green Block)

FLACS utilises a cartesian based grid system which means all cells are represented as cuboids. When the geometry is mapped to the grid, each grid cell is assigned a 'porosity' value between zero and one to represent the degree of geometry occupancy. A fully open cell has a porosity of one and a fully blocked cell has a porosity of zero. A half-occupied cell will have a porosity of 0.5 applied to the entire cell, implying that it is semi-porous. At the interface between solid geometry and open space, unless the grid perfectly aligns with the geometry edge there will typically be a layer of semi-porous cells. This is practically unavoidable when a circular shape or a diagonal shape is overlaid on a cartesian grid. A semi-porous cell is defined as being partially open to flow but at the same time contains material contributing to congestion and therefore turbulence generation and higher overpressures in an explosion. Consequently, geometry arrangements yielding a high fraction of semi-porous cells, such as a narrow cylindrical pipe cross-section, risk introducing artificial explosion turbulence.

In order to understand the significance of this issue and to determine the optimal representation of the pipe cross-section a series of test explosions were undertaken using the default cylindrical approach and the following alternative arrangement types:

- A stepped cylindrical shape in which all cells within the geometry were definitively either open or closed;
- A square shaped duct arrangement in which the cross-sectional area was equivalent to the cross-sectional area of an 8-inch pipe;
- A square shaped duct arrangement in which the perimeter was equivalent to the perimeter of an 8-inch pipe;
- A square shaped duct arrangement in which semi-porous cells were applied in the corners only so as to induce a pseudo-cylindrical flow.

In addition, the study assessed sensitivity to the number of grid cells diagonally across the flow field.

The results of this testing confirmed that semi-porous cells have the potential to significantly increase modelled explosion overpressures and must therefore be avoided. Overpressures from the other cases (stepped, equivalent area duct, and equivalent perimeter duct) were within a similar range, albeit with the stepped results slightly lower than the two duct cases which were broadly the same. Due to a combination of caution and practicality to implement, it was decided that a ducting approach rather than a stepped was the most suitable method. Further analysis was then undertaken to determine the size of the ducting to be used.

The vent system pipework was primarily 8-inch diameter but also included a single section of 10-inch diameter pipe. As both equivalent-perimeter and equivalent-area ducts were considered acceptable, this provided a range of acceptable grid cell sizes that could be used. In order to model the expansion/contraction of the pipework during the transition between 8-inch and 10-inch sections it was desirable to increase the number of cross-sectional cells uniformly to avoid introducing disturbances. In this case an increase from 5 cells to 7 cells was applied which further constrained the potential grid cell size that could be used. Table 1 summarises the size ranges for each duct type and pipe diameter. Based on this analysis a grid cell size of 0.032m was chosen as the basis for the study and all geometry items were developed with reference to this cell size.

Table 1: Summary of grid cell size options based on pipe diameters and duct sizing approximations

Pipe Diameter (Inch)	Duct Arrangement	Number Cells	Equivalent Cell Size (m)	Acceptable Cell Size Range
8	Equivalent Area Equivalent Perimeter	5 5	0.036 0.032	0.032-0.036
10	Equivalent Area Equivalent Perimeter	7 7	0.032 0.028	0.028-0.032

Scenarios

The feasibility of generating a flammable environment within the vent system was uncertain. Even less certain was the nature of how any flammable region would appear in terms of size, location, and gas concentration. Given the level of uncertainty and the desire to be cautious, it was decided to use a worst-case basis of a 100% fill of the vessel and the vent pipework with an idealised stoichiometric gas mixture.

Two different ignition cases were selected. Ignition at the vent tip was considered to be the most plausible ignition location, due to lightning strikes for example. As an alternative limiting case, ignition within the vessel was also considered.

A light methane-rich gas was selected as the most appropriate fluid type to be used.

The simulations were modelled from ignition until the explosion had concluded and the available fuel had been consumed during which time the peak overpressures and forces were observed. This was generally followed by a longer duration depressurisation phase as the system vented during which the forces tended to remain relatively steady.

Force Calculation

The internal surfaces of the vent pipe system were covered with square shaped pressure panels with a side length of one pipe diameter. The use of a square shaped duct system enabled clear differentiation between the pressures exerted in different directions. The pressure was output from the simulation at every panel as a function of time. Force was then calculated by multiplying the pressure by the panel area.

In a given section of pipe, each panel was paired with the opposite panel. For an X-orientated pipe section this would mean numerous pairs along the pipe length in the Y and Z directions, and a single pair at the opposite ends of the pipe in the X direction.

The differential forces (or out of balance forces) in X, Y, and Z were calculated using these panel pairs for every time step. Given the nature of the flow along the length of the pipe, radial differentials were found to be fairly small as the forces exerted outwards by the explosion pressure wave tend to be almost uniform and balanced. Conversely, axial differentials (i.e. at the bends of the pipe) were found to exhibit significant differences, as might be expected, as the flow at one end of a pipe section can be different to that at other end at a given point in time during an explosion. Consequently, for use in the structural modelling the force of interest on a given section of pipe was taken as the net axial differential force at the bends as a function of time, with any contribution from the radial differential forces along the main pipe length sections discounted. As such the derived forces were dictated by the pressure and momentum exerted where the flow changes direction at the bends where significant out of balance forces could endure.

Differential Force Results

The differential force time history was plotted for each of the eleven sections of pipe as shown in Figure 3 and Figure 4.

For the tip ignition case, following ignition, the burning proceeded in an almost laminar fashion through the fuel in the vent pipework almost as far as the vessel, at which point the rate of burning suddenly accelerated. This slow burning phase took almost 30 seconds to occur and because of the very slow burning rate the resulting overpressures and corresponding forces during this phase were negligible. Therefore, this section of the time-history was removed from the profile that was introduced to the FEA analysis to help improve the efficiency of the FEA simulations.

The differential forces applied to each pipe section appear to experience two distinct phases of behaviour. There is an initial dynamic phase in which the forces can oscillate wildly and during which the peak differential forces occur. This is followed by a more stable phase in which the differential forces are broadly constant over a longer period, described here as the steady state phase. In terms of input to the FEA analysis, this led to the development of two datasets:

- Dynamic Dataset – A force time history to represent the variable differential force on the pipe section over time;
- Steady State Dataset – A single time independent force to represent the relatively stable differential force on the pipe section.

Table 2 summarises the key forces within each phase and for each ignition case for each pipe section. For the dynamic phase, the max is taken as the peak differential force (in absolute terms) occurring at any time during this period, which may be essentially instantaneous. Conversely, in the steady state phase, the single force will be sustained over a long period of time and can be considered as time independent. Note that in the FEA modelling of the dynamic case the full time history was modelled not the single value in peak value provided in Table 2, whereas for the steady state case the FEA model did use the single value provided in Table 2.

Table 2: Summary of maximum absolute differential forces predicted on each pipe section for the vessel and tip ignition cases and during the dynamic and steady state phases

Pipe Section ID	Vessel Ignition Case Absolute Force (N)		Tip Ignition Case Absolute Force (N)	
	Max Dynamic Phase	Steady State Phase	Max Dynamic Phase	Steady State Phase
1	29747	7662	11174	7554
2	34678	1863	4215	1316
3	36668	1333	5283	1451
4	31803	330	3189	145
5	19673	819	4348	1030
6	13957	877	2496	760
7	21495	1089	4281	434
8	13730	515	3692	1084
9	6444	601	4020	1173
10	3663	379	3980	866
11	3352	100	2414	333

The following observations have been made from the force results in Table 2:

- The forces from the vessel ignition case are significantly larger than those of the tip ignition case. As the tip ignition case yielded relatively little force until the burning reached the vessel, in some respects both scenarios are examples of burning a vessel full of gas. The only difference is that with the vessel ignition case gas within the pipework is being burnt and creating local overpressure pockets at the same time as the vessel is trying to depressurise, whereas in the tip ignition case the pipework is clear of burning when the vessel depressurisation occurs. These pockets of local overpressure within the pipework are what leads to pressure pulsation within the pipework and the larger forces observed with the vessel ignition case;
- Forces during the steady state phase are generally of a similar magnitude for both ignition cases. As the steady state phase represents a relatively stable period of vessel depressurisation, and in both cases the quantity of material consumed within the vessel is the same, the corresponding forces appear to be largely similar;
- The larger forces are generally associated with the longer pipeline sections, most notably Section 1 which is the vent stack, and also sections generally further from the vessel (i.e. lower pipe sections numbers). The longer the pipe section the greater the duration between flow at either end and therefore the greater the potential force differential overall.

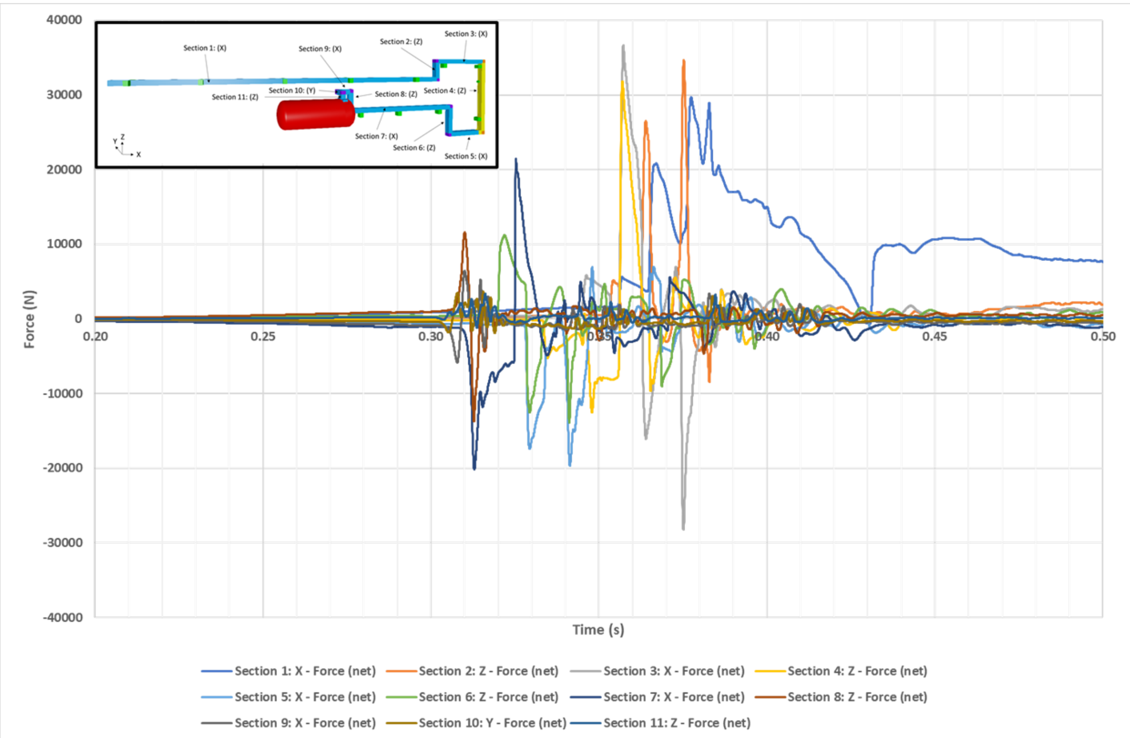

Figure 3: Differential force time histories for each pipe section – Vessel ignition case

Figure 4: Differential force time histories for each pipe section – Tip ignition case

Structural Response Modelling

Objective

The aim of the FEA modelling was to assess the stress response of the pipe supports when subjected to loading associated with the explosion events and to determine what, if any, impact this has on the integrity of the support system and the potential for the pipe to become unrestrained.

3D Model, Meshing, and Materials

A representative 3D model of the vent system was constructed in the SolidWorks FEA package [1]. The model included the knock-out drum, vent pipework, the pipe supports, and vent stack. The supports connecting the vent stack are as pairs either side of the vent pipe at five locations vertically up the stack, denoted 'V1-2' to 'V9-10'. The 6 supports along the mainly horizontal section pipe upstream of the stack, denoted 'H1' to 'H6', consist of two parts: one physically in contact with the pipe referred to as the 'Support'; and the other connecting/mounting part referred to as the 'Foot'.

Each component part was assigned a material type with associated properties as summarised in Table 3.

Table 3: FEA model material properties summary

Material	Parts	Elastic Modulus (N/mm^2)	Poisson Ratio (-)	Shear Modulus (N/mm^2)	Mass Density (kg/m^3)	Tensile Strength (N/mm^2)	Yield Strength (N/mm^2)
ASTM A333 Grade 6	Pipe	220000	0.3	77000	7861	415	240
API 5L Grade B	Horizontal Support	220000	0.3	77000	7850	414	241
Steel Type 5	Foot	205000	0.3	78846	7850	490	355
New Structural Steel (S235)	Vent Stack	205000	0.3	80000	7850	340	195
API 5L Grade B	Vertical Support	220000	0.3	77000	7850	414	241

Meshing was undertaken to convert the 3D model into a system of tetrahedral elements for which the load cases could be solved. A blended curvature-based mesh was applied to the model as this type of mesh adapts well to geometry with areas of curvature and can automatically resize the elements without the need for additional mesh control such as around finer geometry items. This mesh type was chosen after the standard mesh was found to be incompatible with the complex assembly of parts representing the pipe supports.

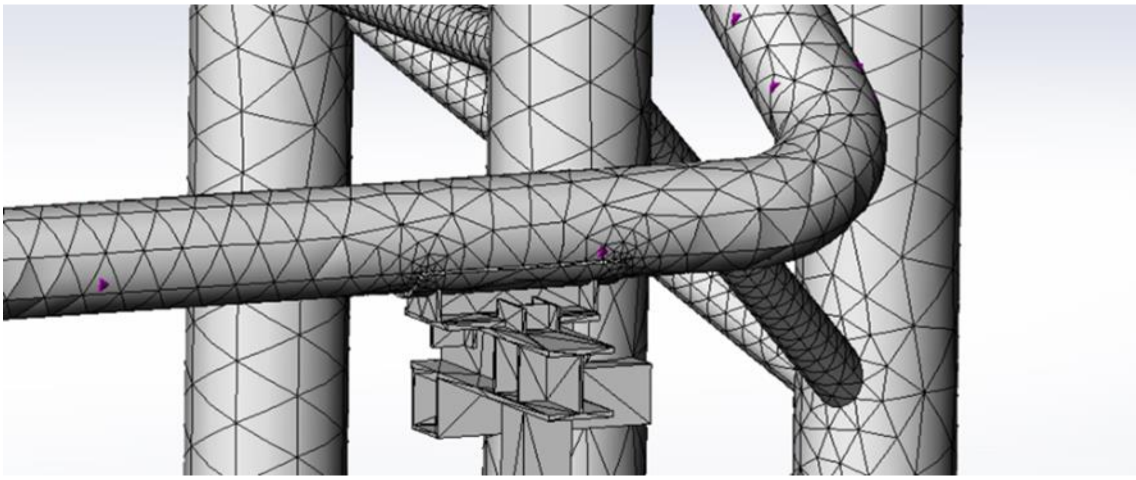

Figure 5: Example of blended mesh on the vent pipe, pipe support, and vent stack

A number of assumptions were made in the build of the FEA model, in general to simplify the model to enable meshing and to reduce the computation time which can grow exponentially for very complex geometry. These assumptions include:

- Areas of pipe curvature were assumed to have the same material as the bulk of the pipe;
- All feet of the system were assumed to be fixed in place;
- Welded components were assumed to be completely bonded to each other (welds themselves are not modelled in SolidWorks);
- The pipe was assumed to have a constant 8” diameter;
- The knock-out vessel was assumed to be a fixed cylinder;
- Flanges and other protrusions/extrusions were omitted from the pipe body;
- The pipe support section ‘H1-Foot’ was meshed as part of the trellis (to assist geometry functionality).

Scenarios

Four scenarios were modelled with FEA in which the forces on each section of pipework derived from the explosion modelling were applied to the structure as either a force time history (dynamic case) or a single force (steady state case):

- Vessel ignition case force time history per pipework section (the dynamic case);
- Vessel ignition case continuous force per pipework section (the steady state case);
- Tip ignition case force time history per pipework section (the dynamic case);
- Tip ignition case continuous force per pipework section (the steady state case).

Stress values were extracted from the modelling as a time history averaged across each component of interest. As averaging was applied across the component, consideration was given to the possibility that results at the sub-component level may differ significantly from the average, and in theory it is possible to continually sub-divided into smaller pieces and further analyse for points of stress (albeit with significant computational expense). However, a sensitivity test was performed to validate this approach and it was determined to be suitable and that potentially damaging stress values were not being overlooked.

Results

The stress output from the FEA modelling was the Von Mises Yield Stress. The Von Mises is not a true stress but a theoretical value that allows comparison between tri-dimensional stress and uniaxial yield limits; essentially this means the model output can be directly compared to the material’s yield stress to determine if a failure is likely to occur.

Dynamic results for the vessel ignition case are shown in Figure 6 which also includes the yield stress of material S235 which had the lowest yield of all the materials considered in this study. All of the component stresses were predicted to be below the yield threshold by at least one order of magnitude. From Figure 6 it can be seen that the component with the highest predicted stress was the H3 support (orange curve) which is broadly in the middle of the horizontal section of pipework.

Dynamic results for the tip ignition case are shown in Figure 7 and are generally below those of the vessel ignition case. Once again, the component with the highest stress was the H3 support.

The highest and lowest Von Mises stresses for each dynamic case are summarised in Table 5 3. For both cases the component with the lowest predicted stress was the V9-10 pair of supports, located at the top of the vent stack.

Table 4: Maximum and minimum Von Mises stresses for dynamic cases

Ignition Case	Highest Von Mises Stress (MPa)	Component	Lowest Von Mises Stress (MPa)	Component
Vessel	8.17	H3 - Support	0.59	V9-10 Support
Tip	3.83	H3 - Support	0.04	V9-10 Support

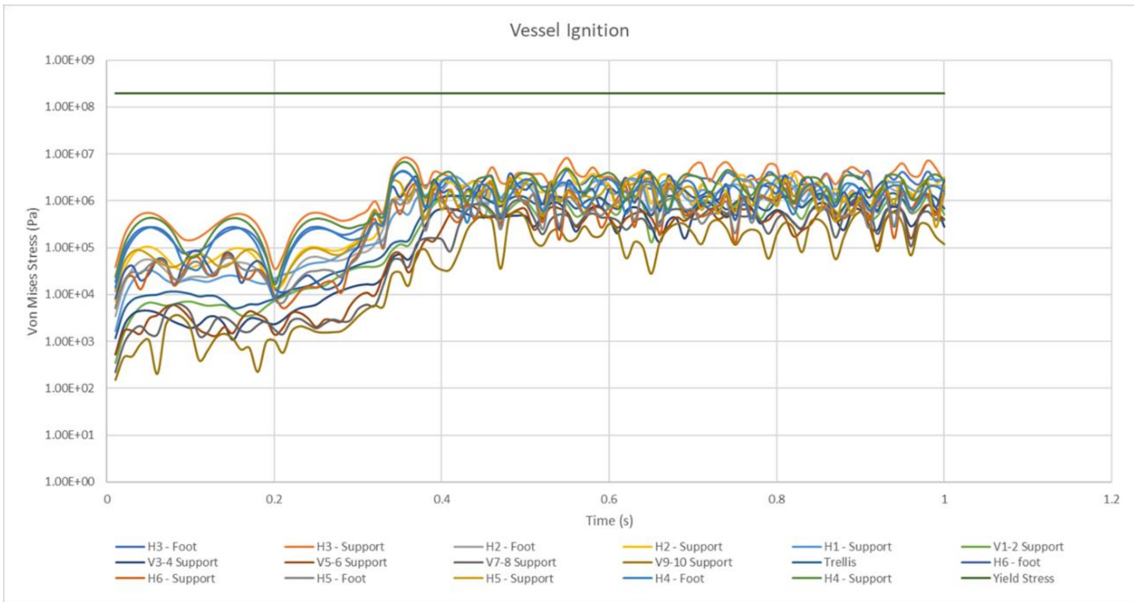

Figure 6: Von Mises stress time history - Vessel ignition dynamic loading case

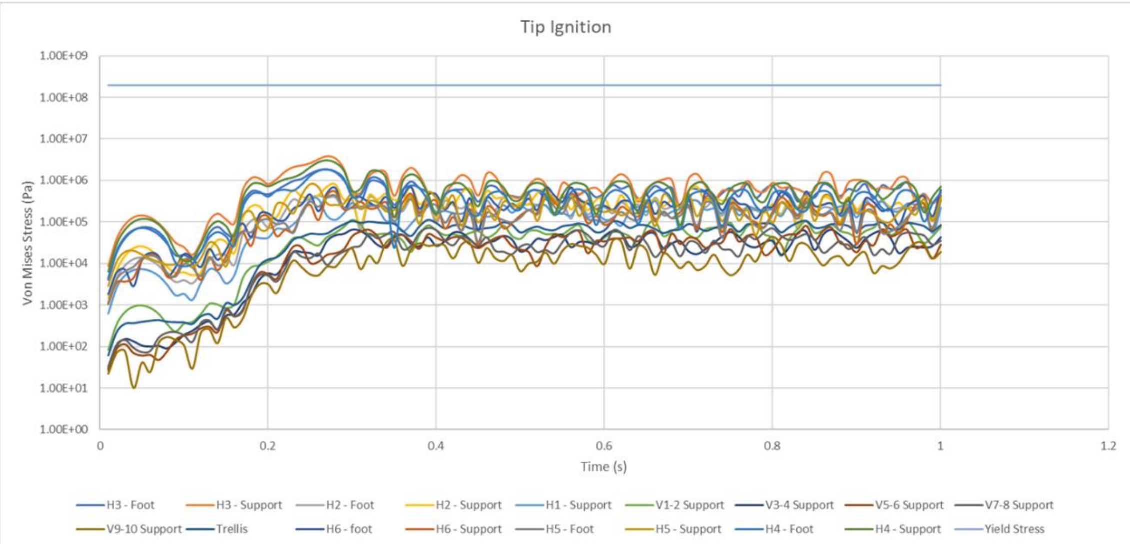

Figure 7: Von Mises stress time history - Tip ignition dynamic loading case

Results from the steady state studies are shown in Table 5. As with the dynamic cases the component predicted to experience the highest stress was the H3 support, whilst the component experiencing the lowest stress was the trellis structure itself. None of the stresses predicted for the steady state cases exceed the minimum material yield threshold and again are typically at least one order of magnitude below.

Table 5: Von Mises stresses for steady state cases

Part	Von Mises Stress (Pa)	
	Vessel Ignition	Tip Ignition
H6 -Foot	3.87E+05	4.06E+05
H6 - Support	1.50E+05	2.61E+05
H5 -Foot	8.83E+04	7.90E+04
H5 - Support	1.20E+05	1.51E+05
H4 -Foot	5.73E+05	5.04E+05
H4 - Support	1.09E+06	9.88E+05
H3 -Foot	6.71E+05	6.53E+05
H3 - Support	1.30E+06	1.17E+06
H2 -Foot	2.89E+05	3.20E+05
H2 - Support	3.06E+05	3.23E+05
V1-2 - Support	3.91E+05	3.00E+05
V3-4 - Support	2.23E+05	2.14E+05
V5-6 - Support	2.05E+05	2.01E+05
V7-8 - Support	1.81E+05	1.78E+05
V9-10 - Support	1.37E+05	1.35E+05
Trellis	4.52E+04	3.82E+04
H1 - Support	6.37E+05	5.18E+05

With regards to component displacement, in all cases displacements were predicted to be minimal. The maximum displacement of a single component was predicted to be <5mm and more generally the overall displacement of the system was predicted to be <0.1mm.

Overall Summary

There is a degree of uncertainty surrounding the nature of an explosion event occurring within the vent system and in particular with regards to the size and location of the flammable region and where ignition could occur. Nevertheless, explosions from worst-case clouds were modelled in CFD and the resulting forces then modelled in FEA. The corresponding stresses were found to be significantly below the threshold for the structural materials to yield and therefore structural failure was not predicted. Displacement of the pipework was also predicted to be minimal. Therefore, the existing vent system design was judged to be adequate with respect to the scenarios modelled and no design recommendations were considered to be necessary.

As the maximum predicted stresses were found to be more than one order of magnitude below the minimum yield threshold, this implies a significant confidence margin in the results. As such, the failure criterion was considered unlikely to be exceeded by plausible events which would thereby comfortably allow for any uncertainties in the modelling such as the potential for heavier hydrocarbon liquids, alternative ignition locations, or unusual distributions of flammable gas.

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