Stainless Steel Thin Shell Blastwalls, Explosion Relief Panels and Escape Corridors for On and Offshore Applications, Current Design and Future Application

Robert Brewerton

Inoventech Ltd

1 Introduction

The article addresses the use of stainless steel for:

- Offshore blastwalls,
- Explosion relief panels in offshore and onshore gas plant
- Escape corridors (also known As Escape tunnels) installed on long integrated platforms and FPSO's (Floating Production Storage and Offtake platforms)

The products were developed following the Piper Alpha disaster in 1988[1] in which 167 people died, and the new regulatory and standards regime that followed it, and is now applied worldwide.

Two future applications of similar stainless steel technology to fire and explosion risk areas are also explored:

- Fully enclosed prefabricated escape stairways designed for retrofitting to residential tower blocks to facilitate simultaneous entry by fire crew and escape of residents.
- Explosion relieving battery containment systems for use in cars and domestic battery storage systems: this is becoming a serious fire and explosion risk area, especially for hybrid and electric vehicles (EV).

Before looking at the specific products a number of relevant factors are described herein:

- The unique properties of stainless steel together with their application to explosion and fire engineering.
- The mechanisms of vapour cloud explosions and structural response to them.
- How the regulatory and guidance regime that arose out of Piper Alpha successfully lead to significant reduction in the incidence and consequence of vapour cloud explosions offshore, worldwide..

The views expressed are based on over 25 years on project design of topsides blastwalls, escape corridors on offshore topsides and Explosion Relief Panels ERPs in onshore gas compression stations and process buildings. The author has had parallel involvement in platform layout optimisation / FLACS CFD studies for installations in many regions of the world and served for 14 years on the drafting committee for ISO 19901-3 (topsides of offshore installations-accidental events)[2] and parallel research studies on behalf of HSE. He has also participated as an expert witness in major accidents. Opinions expressed here are the author's own opinions.

It will be seen that the mechanisms and regulatory responses to the Piper Alpha explosion are potentially appropriate for new technologies which have not so far been properly assessed.

2 Stainless Steel for Explosion and Fire Resistance

Explosions cause rapid increases in applied loads on structures and are best resisted by energy absorbing structures where gross ductile deformation without rupture can be accommodated.

For fire resistance, strength retention at temperatures around 1000°C is valuable together with ductile deformation capacity as fires cause gross distortions of structures.

For fire and explosion resistance at large and small scale the properties of stainless steel are particularly applicable, namely:

1. High strength
2. Ductility and high strain capacity
3. Durability and corrosion resistance
4. Strength retention at high temperatures

Figure 1 shows how the strength and stiffness of stainless steels compare with carbon steel grade 355.

Figure 2 demonstrates the extreme ductility of duplex stainless steel (1.4362).

Figure 3 shows how stainless steel retains its strength at high temperatures. In relation to the products reviewed here the retention at high temperatures (~1000°C) is of great significance as all the products are configured not to support other significant loads during fire.

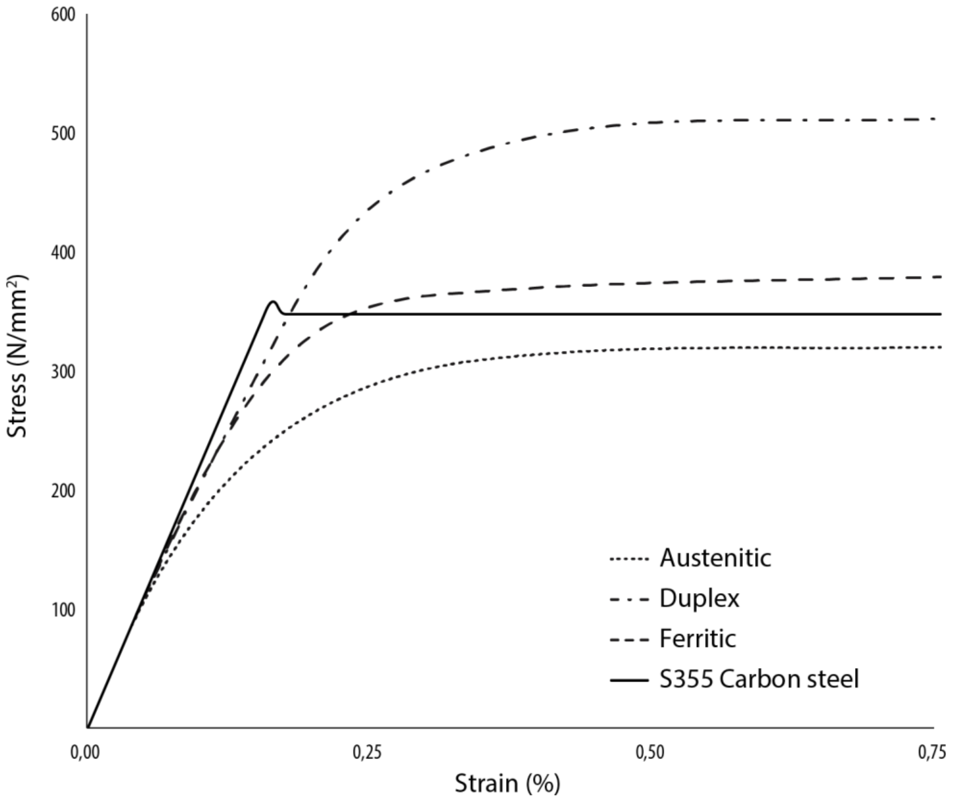


Fig. 1 Stress-strain curves for stainless steel and carbon steel 0-0.75% strain (Design Manual for Structural Stainless Steel, SCI).

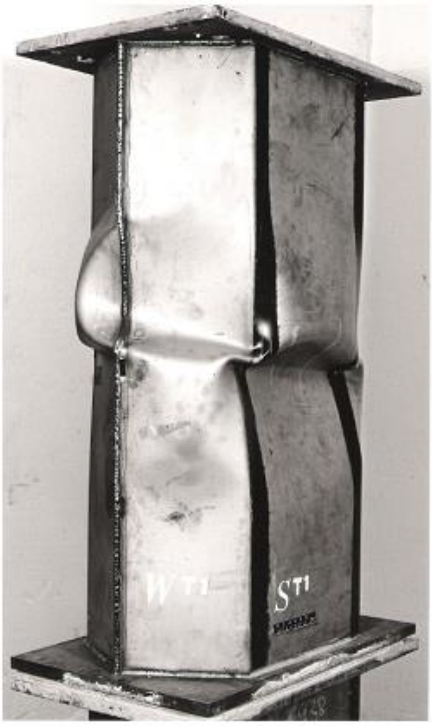


Fig. 2 Full scale crushing test on 4mm thick Duplex stainless blastwall components (Chapman Dowling - Imperial College 1991) shows ductile behaviour without rupture.

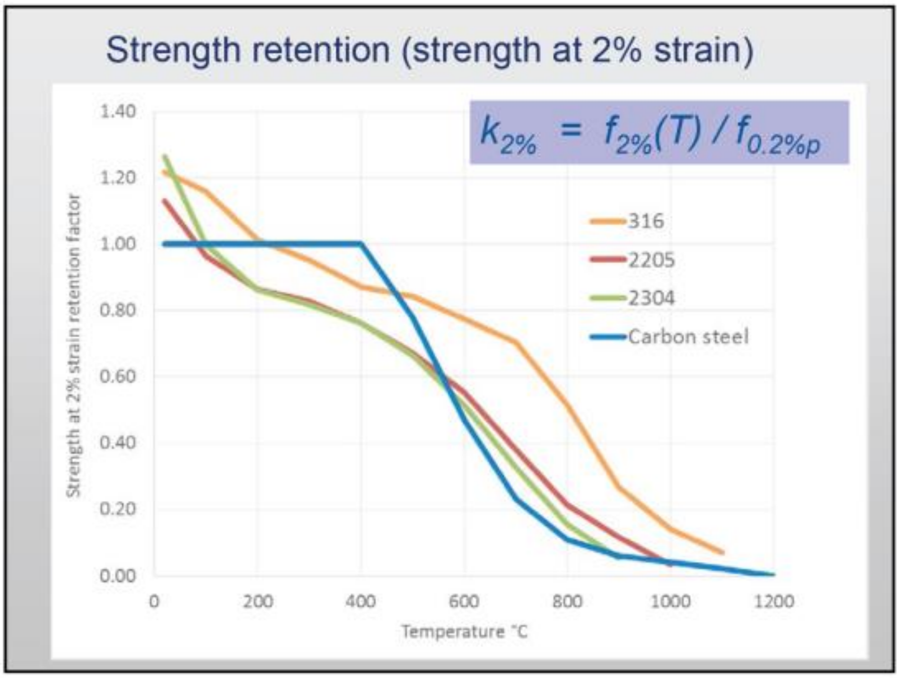


Fig. 3 Strength retention of carbon and stainless steels at elevated temperature[3].

3 The Mechanisms of Vapour Cloud Explosions

In oil and gas plant and chemical facilities the primary accident scenario is explosion followed by fire. Fires can also occur without prior explosion.

Explosion following fire can (more rarely) occur as a result of pressure containment systems for hydrocarbons being heated at a rate which exceeds the blowdown rate of the system affected, leading to bursting of such systems and large fireballs with accompanying projectiles.

Vapour cloud explosions are preceded by a leak of volatile or gaseous hydrocarbons that mix with air to create an explodable vapour cloud. An explosion occurs when a part of the cloud encounters an ignition source (a spark or hot surface). Afterwards there is a fire as the leaking vapour continues to burn until the inventory of leaking vapour is exhausted.

In open or congested open environments the forming cloud migrates according to the local instantaneous wind regime. In enclosed spaces the cloud will gradually fill the space and become more concentrated with hydrocarbon gas or droplet mists. Highly rich mixtures will not ignite due to lack of oxygen, similarly rarefied mixtures will not ignite either due to inability of the mixture to sustain burning.

It should be understood that good design and operating practice can reduce the risk of ignition so that many clouds that form actually dissipate before being exploded. Control of ignition probability is therefore a useful mitigation measure. However the bigger the cloud is, the more likely it will be that it encounters an ignition source and the bigger the explosion will be.

So a general rule is to arrange the facilities so that probable cloud sizes are reduced by good design practice at the outset (good natural ventilation). This is a 2nd form of mitigation.

A special form of this improvement is reducing the size of explodable inventory that can be released in an accidental event. This form of hazard minimisation is a 3rd mitigation method.

Compartmentation involves the separation of hazardous zones into smaller volumes, each with a smaller number of leak points and ignition sources and smaller cloud volumes. This is a 4th mitigation method. Such spaces are open ended with fire resistant blastwalls at their sides and blast and fire-resistant decks and are most effective in longer and narrower topsides process areas.

Where buildings are enclosed the boundary walls can be made explosion and fire resistant for effects outside the buildings, and can conserve heat and reduce operational noise impacts at neighbouring communities. To reduce the confinement for internal explosions the boundary walls or roof can be provided with vent panels that open in response to development of explosion pressure inside the building (Explosion Relief Panels or ERPs). This is a 5th Mitigation method.

When the vapour mixture starts burning from a point source, the flame front radiates outwards from that point. When it encounters obstacles they will distort the flame front and increase its surface area. This increases the conversion rate from cold gas mixture to hot burnt products which will occupy approximately 8 times more volume. This causes the flame front to accelerate and encounter further obstacles causing a positive feed-back mechanism that causes the pressure in the area to ramp up and can easily increase the explosion pressure by a factor of 1 to 2 orders of magnitude.

This was a major aspect of the Piper Alpha investigation. This flame acceleration effect was known at the time but not thought to be as important as it turned out to be. Offshore platforms and onshore chemical plant do have dense congestion as shown in Figures 4 and 5.

It is not actually possible to change the amount of congestion in a project without changing the project's overall function, though one can use process equipment that includes fewer obstacles. This is a 6th Mitigation method.

One can change the shape of the congested zone and divide it into subzones separated by uncongested gaps and this does reduce explosion overpressures. This is a 7th mitigation. This has been known about and applied for onshore plant for decades.

However well the mitigation is done there will invariably be a residual risk of explosion in a hazardous plant, so to reduce consequence one can distance people from hazard, and provide escape to safe areas well away from hazard. This is a 8th Mitigation action.

Where such escape routes cross other areas which contain explosion hazard one can use fire and blast resistant escape corridors or tunnels. This is a 9th mitigation method.

Summary of mitigation methods for explosion

1. Reduction of ignition risk
2. Minimisation (of explosive inventory released in an event
3. Improved ventilation
4. Compartmentation to reduce event size
5. Improved venting of enclosed spaces (use of ERPs)
6. Selecting equipment which creates less turbulence (fewer obstacles)
7. Use of empty gaps in large process zones
8. Improved escape to more distant safe havens
9. Improved means of escape (protected escape routes)

The products that which have a significant role for the use of structural stainless steel and have been used and described below relate to mitigation methods 4, 5 and 9.

The action of Flame Acceleration is the main driving force to increasing explosion severity in congested areas, as most offshore platforms and refineries are. To calculate what the peak developed pressure would be for a complex geometrical environment requires the use of a Computational Fluid Dynamic (CFD) computer programme and the one that is used worldwide is FLACS. FLACS was developed and is marketed by CMR GexCon in Norway).

Fig. 4 Multiple fixed platforms Buzzard development in UK N. Sea, from left to right: tie- in Satellite platform, Drilling and Risers, Process, Utilities and accommodation, all bridge-linked in 100m water.

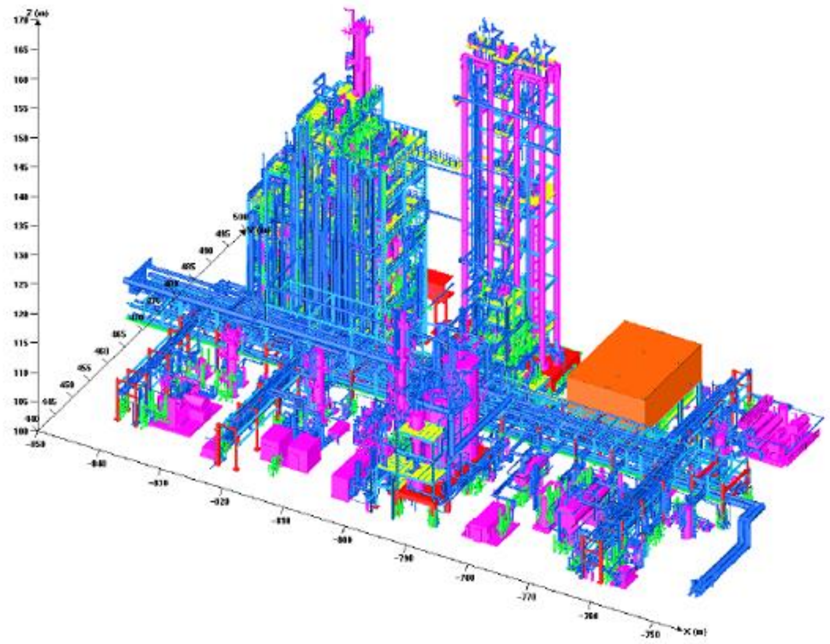


Fig. 5 FLACS geometry model of a part of an onshore chemical plant.

4 Development of Post-piper Alpha Regulatory and Guidance Regime and Setting Design Accident Loads

The Cullen report into the Piper Alpha disaster was initiated by UK government in 1988. The findings were implemented by act of parliament. Piper Alpha was one of four gas explosion accidents in the North Sea in 1988. The previous 12 years had seen sudden and rapid development of the North Sea, an activity which was undertaken using the "best practice" and technology available at the time.

The follow up to the Cullen report by Industry, saw the HSE set up as regulator, taking over from the department of energy. The main measure has been to impose a requirement to back up each project with a bespoke Safety Case prepared by the facility owner, a role defined as the Duty Holder.

Offshore oil installations are not standard repeatable designs, they are all bespoke.

The Safety Case has two phases, Design level and Operating and the safety case has to be approved by the HSE and it is illegal to operate an installation without an approved safety case. Operators have to implement a through life Safety Management System which includes the design stage.

SCI, who is the organisation setting up this conference, was chosen at the start as guidance writer and, since 1988, has been the research and seminar focal point, organising conferences and research. The part of SCI dealing with this is the Fire And Blast Information Group (FABIG) and is continuing this role, now on a worldwide basis.

The measures implemented by the Cullen report were highly successful in reducing the incidence of offshore explosions and their consequences both in the UK and world-wide, as the measures were adopted world-wide.

The research side, funded by Joint Industry Projects (JIPs) through the 90's sponsored a major series of large scale explosion and fire tests to fill evident gaps in industry's knowledge base and calibrate explosion software such as FLACS and equivalent fire simulation software. The main computer models in both areas were Norwegian but as the response to the disaster was an international one this presented no particular problem.

In looking at applications of predictive software it became clear that there was a large range of potential explosion scenarios and consequent peak explosion pressures that needed to be ranked by a logical process. The process adopted was a probabilistic one based on leak and ignition frequencies found by reporting from industry, a continuous and ongoing reporting process hosted by the HSE in UK and its counterpart in Norway.

It became clear that some accident scenarios would lead to explosion loadings that would be impossible/impractical to design for.

The agreed action was to develop designs where risk and consequence were As Low As Reasonable Practicable (ALARP) and this is now built into ISO standards and regulations worldwide. In ISO standards it was stipulated to generate explosion load cases for structural design, which the structure and critical equipment would have to withstand. The adopted probability threshold was a frequency of 10^{-4} per year.

The load cases that corresponded to the threshold frequency became defined as the Design Accident Load Case(s) (DAL) and the document defining these became the interface between the probabilistic loading evaluation and the deterministic load cases that could be checked against the established structural standards.

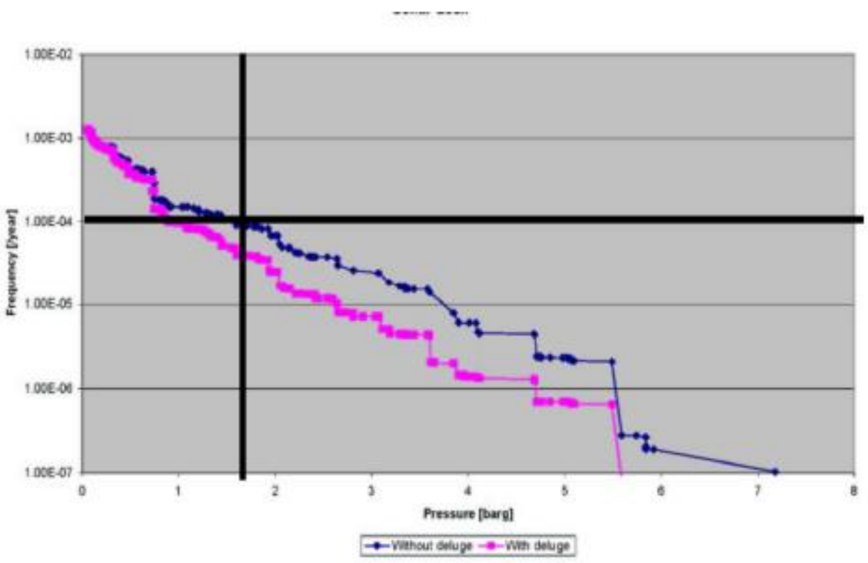


Fig. 6 **Typical panel pressure exceedance curve (3m x 3m panels) (Blue graph is the applicable one, the pink line is the effect of water deluge during the explosion).**

Figure 6 shows a probabilistic load-exceedance curve for a selected zone of a structure (e.g. a wall). The codified design exceedance level (10^{-4}) is shown by the horizontal black line and the design peak value of load is where the black line crosses the blue graph. (The pink one is predicted explosion pressure with water deluge acting).

Explosion response analysis requires the time-history of the load pulse to be defined. Though quite complex for any particular scenario it can be usually be simplified to an isosceles triangle shape identified by its height (in mbar) and duration in milliseconds. For offshore installations duration is typically 50-150ms.

The structural and equipment response side and design practice aspects are equally important as, having defined what the explosion and fire loadings are, it is necessary to build the structure and equipment so that it will survive the necessary accidental loadings.

The structural response aspects included guidance and standards which referred to structural design codes (Eurocode 3) and ISO standards also allowed primary reference back to AISC codes and other national standards.

Guidance on structural response includes how to use advanced computer analysis as this sidesteps standards in many ways. Such analysis is routine in the offshore oil and gas industry and has been used to support the stainless steel products described in this paper.

The large scale fire and explosion tests carried out in JIPs concentrated on loading aspects. The fire tests did demonstrate the effectiveness of stainless steel, but also demonstrated carbon steel as well, though greater thickness are required than for stainless steel. Other research projects looked into response of materials and structural components. Those relevant to the structural use of stainless steel are referred to in this paper.

4.1 The outcome of the post-piper Alpha Efforts

Achieved Goals 1

1. A new regulatory regime led by the HSE where operators are required to implement a safety management system.
2. A realisation that all possible accidental events cannot be coped with.
3. A Goal-setting regulatory regime based on the ALARP principal, supported by probabilistic analysis.
4. The requirement for a safety case for all installations.
5. The goal of inherently safe(r) Design.

Achieved Goals 2

The route to inherent safer design by optimum platform layout is achieved by:-

1. Removal (of Hazard) Including attenuation
2. Distancing (people from hazard)
3. Minimising (hazard) to reduce consequence
4. Strengthening to improve blast resistance
5. Improved means of escape

5 Stainless Steel Blast Walls

Blastwalls are used on offshore platforms to sub-compartment areas (a mitigation measure). Figure 7 shows a typical arrangement of barriers in a fixed platform (Blast and fire resisting barriers are shown in red). Figures 8 and 9 show cross-deck walls on an FPSO

Blastwalls are mostly top and bottom supported and, thanks to the use of compliant top and bottom supports they do not participate in carrying dead loads, other than the self-weight of the wall. The advantage of this is that during a fire the required strength retention is less than 5% of cold strength so that temperatures can rise to 1000°C without the need for passive fire protection (see Figure 3).

An exception is the upper wall shown in Figure 8 which has vertical carbon steel beams and horizontal spanning corrugated stainless steel wall panels with compliant end supports.

Weight is an issue with many topsides designs as every kg of structure added is a kg of equipment that cannot be added hence structural economy is important to overall project economics.

Bulkhead walls (the main alternative to prefabricated corrugated walls) do participate in the overall structural support of the platform facilities. Bulkhead walls therefore do generally need passive fire protection.

The blastwalls, escape tunnels and emergency escape towers discussed in this paper are all integrated into structural frames that provide alternative load paths for keeping the platform (or building) up. These are mostly located on the fire-protected side of the wall or are themselves fire protected.

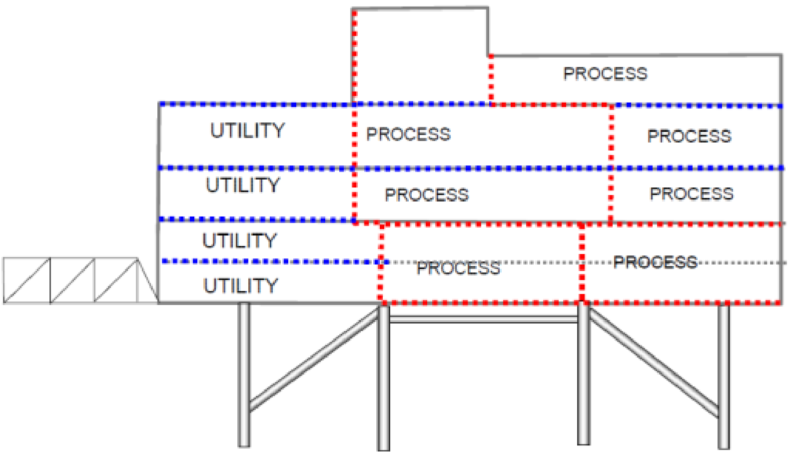


Fig. 7 Positions of Blast and Fire barriers and blastwalls in a large process topsides .

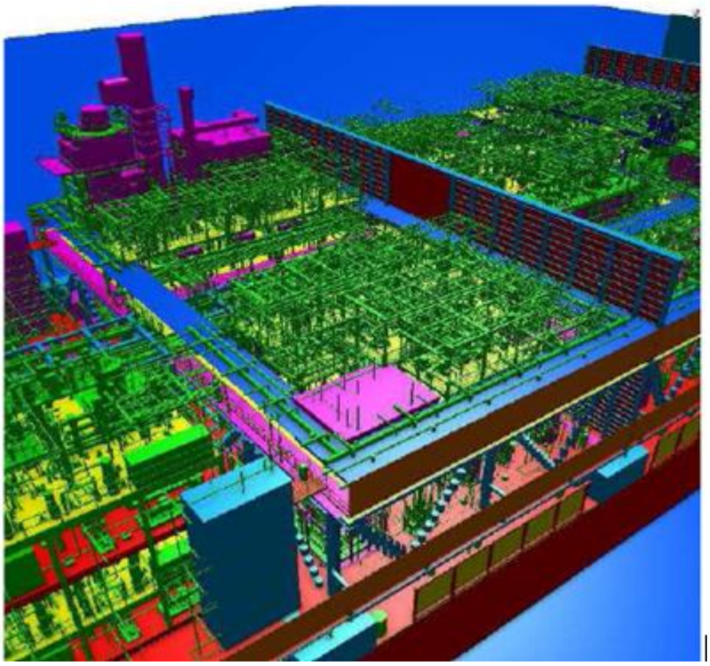


Fig. 8 Cross-deck blastwalls on an FPSO (note escape tunnel at bottom right).

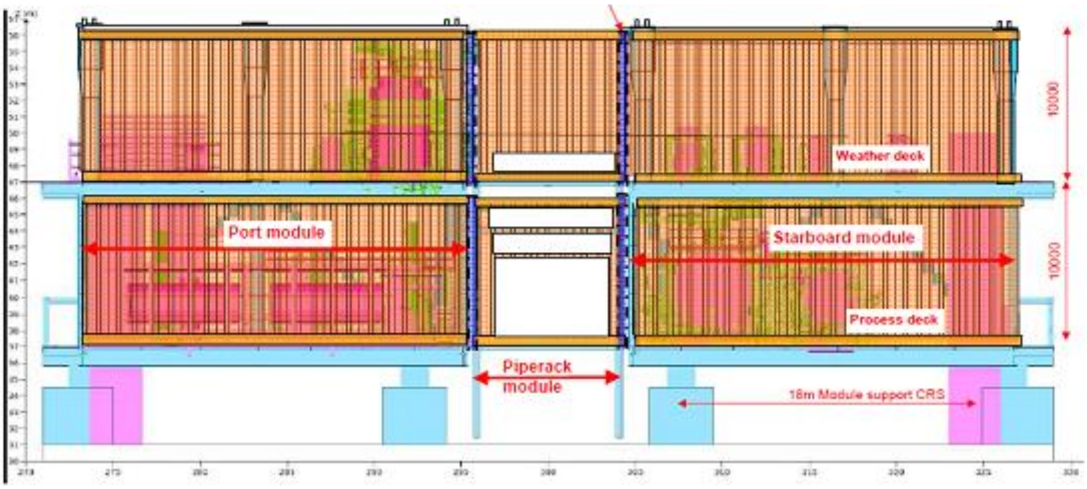


Fig. 9 Cross deck blastwall on an FPSO.

Fig. 10 Stainless steel blastwalls in an offshore module.

Figure 11 shows a prefabricated duplex stainless steel wall panel in 9mm thick duplex stainless steel for a 13m high blastwall.

Fig. 11 Prefabricated Duplex stainless steel prefabricated panel ready for shipment to Australia part of a 13 m high blastwall).

Figures 12 and 13 show the Non-Linear FE model (LSDYNA) for a 9m high wall. The wall is made up of prefabricated panels approx. 2.2m wide (two corrugations wide). It is supported only at the top and bottom and has compliant connections to the deck via bent-up carbon steel angles. The wall is an all-welded structure and site connections to the decks are carbon-steel to carbon steel removing the dissimilar metal weld from the main contractor's scope. This also raises the dissimilar metal joint above the deck so that standing water does not occur in service.

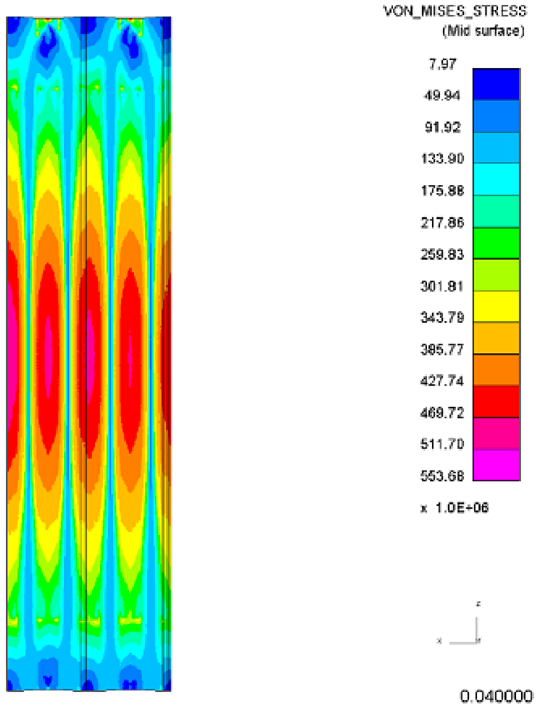
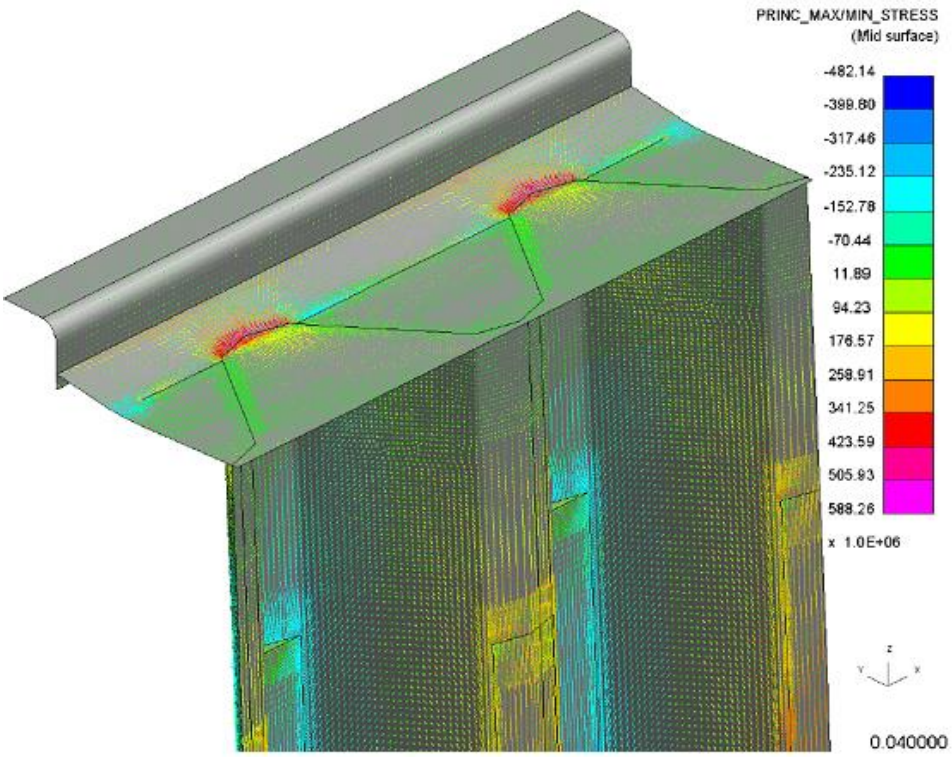


Fig. 12 LSDYNA model for a Non-linear analysis of a 9m high wall. The wall is supported at the top and bottom only. This view shows von Mises equivalent stress at peak of response.



Fig, 13 Close-up of upper part showing compliant top support and mesh refinement in NLFEA model.

5.1 Design methodology and standards

The overriding design standard for offshore installations is ISO 19901-3[2]. In Europe and some Far East countries the overriding structural design code is Eurocode 3, in USA it is AISC. These codes (apart from ISO 19901-3) are not ideal or sufficient because they do not give enough guidance on ductile capacity when local buckling at mid-height starts, nor the transverse out-of-plane effects due to local pressure on the plate, or interaction between the two effects. A specific design guide for corrugated stainless steel blastwalls guide is FABIG Technical Note 5 “Stainless Steel Blastwalls” published by SCI and sponsored by HSE[3]. It is the reference guide in ISO 19901-3. This guide can also be applied to corrugated carbon steel walls.

The design of the walls presupposes an idealisation of the structure into vertical strips, analysed as beams together with the compliant connections at their ends.

This allows simplified manual calculations based on Eurocode 3 and the Single Degree Of Freedom (SDOF) method, used widely for explosion response design. The method takes account of the dynamics of the short-term load impulse and the transition of the structure from elastic resistance limit to ductile deflection as shown in Figure 14.

Use of Dynamic explicit NLFEA such as ABAQUS or LSDYNA quantifies more accurately the response and shows a small degree of reserve that is missed by the manual methods.

Unfortunately over-simplifications in NLFEA or using inappropriate analysis models tends to be systematically unconservative as incipient critical failure modes like local buckling are either not identified or take place too late in the response. The structural design standards do not cover this area adequately.

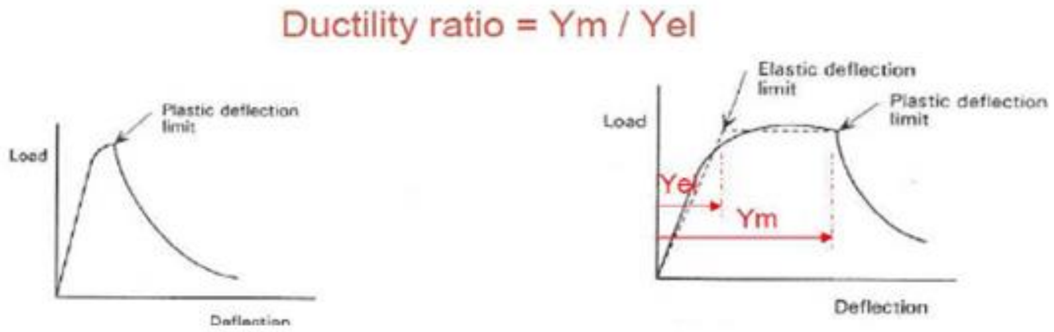


Fig. 14 Elastic and ductile deflections.

Ductile deflection tolerance is defined by the ductility ratio, which is Ym/Yel in Figure 14. In the second diagram the energy absorption of the profile (or beam strip) is the area under the graph and is clearly much greater. This translates into much increased energy absorption and a reduced required quasistatic resistance Rm for the wall for the given applied peak dynamic load Pmax. The ratio Pmax / Rm is the design Dynamic Load Factor (DLF).

A reduced required quasistatic strength reduces the weight and cost of the wall and the reactions transmitted to the support, a further economy of the ductile wall concept.

For a conventional corrugated blastwall with trapezoidal corrugations Figure 15 shows the failure mode. This was established for this example, from experiment and LSDYNA on a duplex stainless steel blastwall.[5]

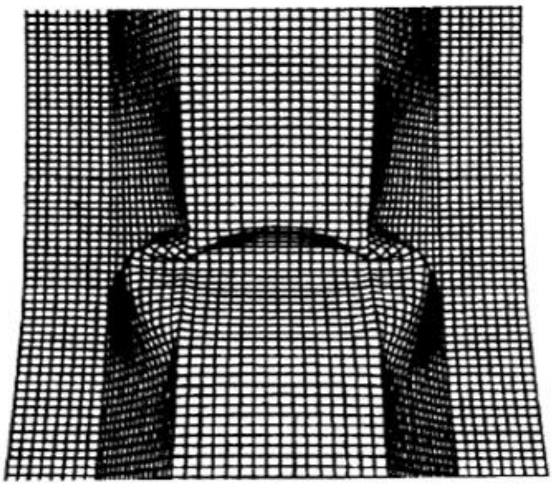


Fig. 15 Failure mode for normal trapezoidal corrugation with b/t ratio 60.

Improved cross section shapes give better ductility ratio. The proprietary arch profile blastwall as has been used recently in most offshore prefabricated blastwalls in N Sea and Azerbaijan. It has superior ductile capacity by halving the bucking panel width for the same profile. Figure 18 shows the onset of buckling in an arch profile wall at a ductility ratio of about 4.

The concept was developed by Inoventech Ltd and is a proprietary system covered by international patents.

The double compression flange option in Figure 16 has the added advantages of shifting the neutral axis up so that ductile deformation, when it occurs, occurs on the tension side so that local buckling modes can be avoided. Additionally the web has a larger tensile zone than the compression zone so less tendency to local buckling. This allows the profile to be deeper for the same profile thickness, a major advantage in weight economy terms.

Figure 17 shows a stack of profiles for 3bar long-span profiles for blastwalls destined for Azerbaijan. These are in S355 carbon steel. The figure shows a fabricated profile to the right of the stack.

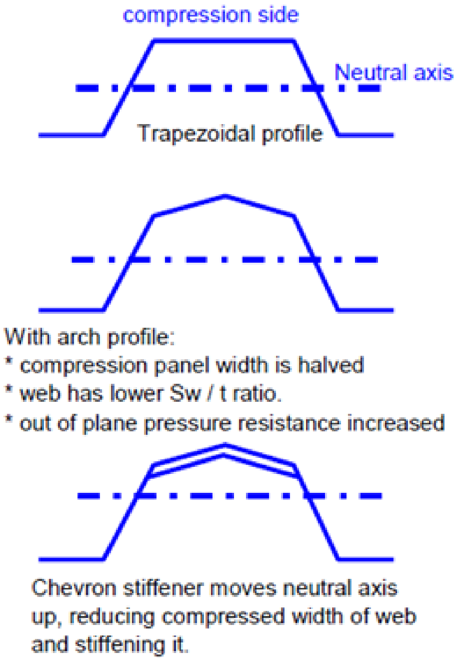


Fig. 16 Patented arch profile blastwall improves post elastic buckling performance.

Fig. 17 Arch profiles for blastwalls destined for offshore Azerbaijan, note fabricated panel on right.

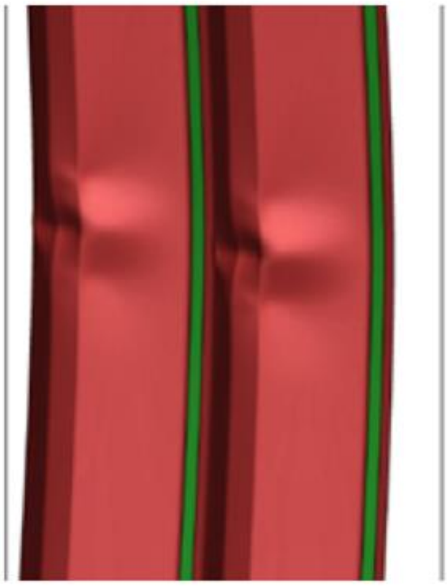


Fig. 18 LSDYNA model of an arch profile blastwall showing onset of local buckling at mid-height: ductility ratio 4 approx.

6 Explosion Relief Panels

The stainless steel concept was developed by Inoventech Ltd and is a proprietary system covered by international patents.

Panels are normally supplied as complete prefabricated cassettes for spanning between main building columns (for walls) or main horizontal roof beams or purlins (for roofs).

It can equally be supplied in the form of a kit of parts and can be applied to roofs like conventional corrugated roof cladding. The concept can equally be applied to winterisation walls on offshore platforms where it may be supplied as perforated panels for weather protection with ventilation (eg for Barents Sea).

For roof panels in areas prone to ice and snow they can be provided with trace heating cables between the insulation and the stainless steel panel.

Figures 19 and 20 show the system applied to a compressor building in France. Figure 21 shows roof cassettes for a gas compressor enclosure for the UK.

In these cases the system was required to provide relief of internal explosions, sound reduction (to reduce external noise) and a degree of resistance to internal fires.

Fig. 19 Stainless steel explosion relief panels installed on a gas compressor building in France.

Fig. 20 Explosion Relief panels viewed from inside, note foil covered high density rockwool insulation for sound reduction and fire resistance.

Fig. 21 7.2m long roof cassettes for gas compressor enclosure (UK).

Fig. 22 Kollsnes gas compression complex for Troll Gas, Norway.

Fig. 23 Kollsnes gas compressor building cladding provides explosion relief for internal explosion (hinged panels for projectile avoidance) and resistance to external explosions and 43dBA sound reduction.

In these examples the main longitudinal framing is external for the wall cassettes but internal for the roof cassettes. The framing is carbon steel and designed to withstand forces due to explosion effects, which are significant as the relief panels are fully fixed at their mid-line to the support framing and designed to hinge in an explosion so that they do not blow off in an explosion. They would otherwise become projectiles with risk of injury to persons outside the building and damage to other nearby facilities, which might escalate the consequences of an explosion within a building.

Figure 23 above shows a gas compressor building in Norway and Figure 22 shows the arrangement of compressor and process buildings at that site. The hinged explosion relief panels are of a different design and material but serve a similar purpose. In this case the whole external wall area (apart from the bottom 2m) is covered with relief panels.

One of the reasons why the proportion of wall area covered by panels is much larger in Figure 23 is that the a parameter for effective venting and provision of relief panels is the buildings Av/V ratio, where Av is the effective vent area and V is the volume of the building, As the buildings become bigger the percentage of wall coverage increases to maintain Av/V ratio.

Another issue is the degree of equipment congestion inside the building as this dictates the rate of burning of the internal vapour cloud and the peak pressure reached in the building once the panels have opened. Figure 20 is a particularly good example as the equipment is configured so that the internal congestion is low so that developed explosion pressures inside the building are minimised.

Figure 24 shows a transverse section through stainless steel relief panels largely similar to those shown in Figures 19 to 21. In Figure 24 the framing is fastened to the building's purlins. These framing members are made of small dimension rectangular hollow section members in S355 carbon steel.

For the designs in Figures 19 to 21 the carbon steel framing is more substantial and the panels are supplied as fully framed and insulated cassettes whish are capable of spanning the full 6m between building columns. For the roof panel cassettes in Figure 21 the span is 7.5m and cassettes are bolted into a 9m x 7.5m assembly which can be lifted off bodily to facilitate major maintenance on the equipment inside the building.

In Figure 24 the panel opening behaviour is shown in red. Internal pressure rises in response to the developing explosion inside the building

The panels are fully fixed strongly to the RHS spine beams at their mid-line. Figure 25 shows how the outer long edges of the panels are retained in a slot, which allows the panel edges to slip out when the panels bulge out about 70mm in response to rising explosion pressure from within the building. In this configuration the two intermediate corrugations are supported off the transverse purlins by a sort of screw jack which moves out with the panels in an explosion. They then open like doors.

Typical opening time is 40-50ms for this type of panel but depends upon rate of development of explosion pressure.

An important performance parameter is the release pressure. The design release pressure is normally 50mbar (5kN/m2), which gives a good safety factor against spurious release in storm winds.

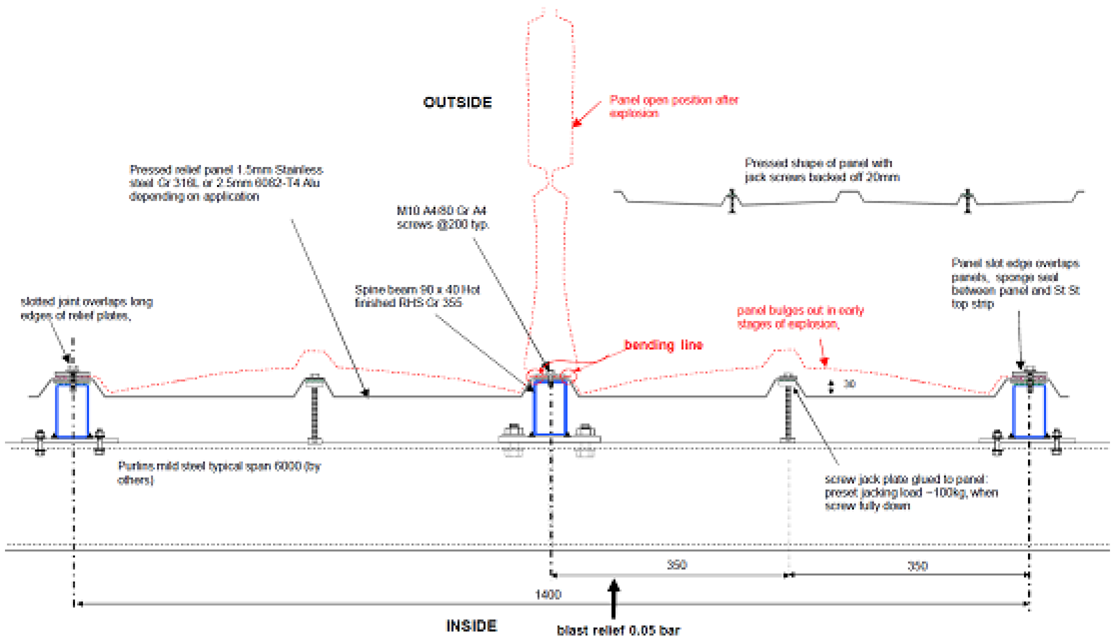


Fig. 24 Transverse section through wall/roof cladding for 1400mm panel pitch.

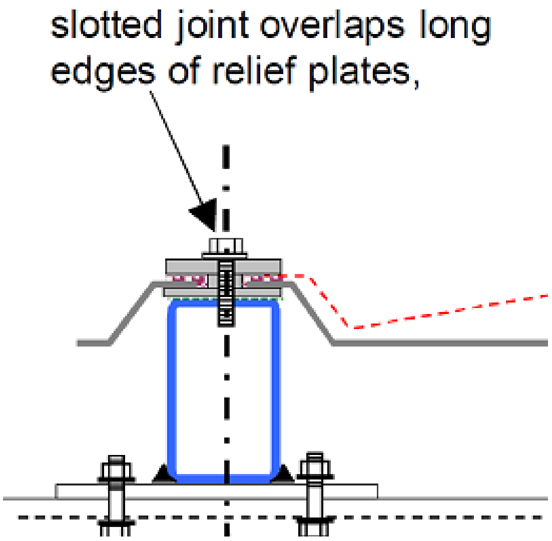


Fig. 25 Panel edge detail showing release method.

Figure 26 shows how the panels would be insulated for fire or thermal efficiency or sound reduction. Where fire is the requirement the insulation has to be fixed to the panels with welded insulation pins.

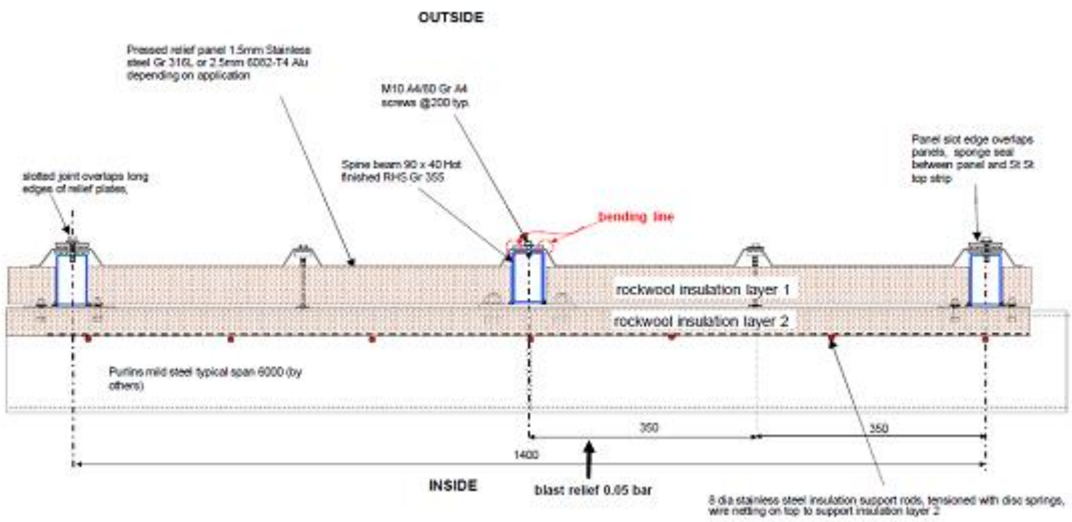


Fig. 26 Transverse section showing Insulation scheme.

The system design is based on full scale explosion tests performed at GexCon's facility in Norway. Full design and technical documentation to FABIG Technical Note 2 "Explosion Mitigation Systems" is provided[6] (FABIG is part of UK Steel Construction Institute). The system is covered by ATEX certification in accordance with "Equipment Or Protective Systems Intended For Use In Potentially Explosive Atmospheres Directive 94/9/EC"[7].

Figures 27 and 28 show explosion testing of the stainless panels in a congested explosion test module by GexCon near Bergen in Norway. The panels were fire and sound insulated with high density rockwool.

Fig. 27 Explosion Relief panel before explosion test.

Fig. 28 Explosion Relief panel after explosion test to 0.5bar.

Summary of advantages of stainless steel for ERPs

1. Good strength / weight ratio enhances venting efficiency,
2. Good corrosion resistance means that plating can be thin, typically 0.7 to 1.5mm without prejudicing service life (no corrosion allowance required),
3. High ductility means easy pressing or profile rolling,
4. Natural fire resistance (subject to fire test).

7 Escape Tunnels

7.1 Basic functional requirements

An escape tunnel can be needed on long installations where operators work at both ends of the installation and at intermediate points along the length. A tunnel provides a protected escape route back to the main safe refuge and the lifeboats.

An escape tunnel needs to have the following features:

1. Weather and sea-spray tightness.
2. Blast resistance.
3. Fire and jet fire resistance for sufficient time for escape.
4. Minimum vent area blockage to surrounding hazardous areas.
5. Sufficient spanning strength and convenience of support positions to minimise the amount of added module steel required to support it (and its fire protection).
6. Sufficient air flowing through it to keep it cool for the required duration of escape and to reduce smoke ingress.
7. Corrosion resistance in marine environment.
8. Movement joints at structural supports, to cater for operational, explosion and thermal expansion / distortion in fire.
9. To be of minimum weight as most applications in which they are used are highly weight sensitive.
10. To be supplied complete as outfitted sub-modules for integration into the topsides as a whole which are transportable many thousands of miles.

To satisfy the main blast and fire resistance functions, the tunnel needs to have a double envelope construction with an outer structure and an inner structure insulated from the outer structure so that heating of the outer envelope does not lead to excessive temperature rise for occupants / escapees. Also important is that the internal temperature rise should not prejudice the inner structure's ability to support the heat-softened outer structure and that heated internal finishes and insulation that do not give off fumes.

There are two ways of doing this. Type 1 is by having the main structural strength of the tunnel as a RHS truss frame and the outer stainless steel envelope as a blast and fire resistant skin: the fixed platform application shown in Figures 29 and 30 is this type.

Fig. 29 Gas and condensate platform for 190m water depth ready for load out on a barge, Note Stainless steel fire and explosion proof escape tunnel all along the side (Type 1).

Fig. 30 Inside view of Fixed platform escape tunnel type 1 in Fabrication at Booth Industries in UK: the internal cladding gives an obstruction free escape route: the steelwork of the internal truss can be seen at the top. The top 300mm of the tunnel is service duct.

The second (Type 2) is by having the main tunnel structure as a stainless steel stressed skin designed for all loadings and the internal truss designed merely to support the stress skin envelope against sagging in a severe jet fire (like a Salvador Dali watch). This type 2 is shown in figure 31 mounted on an FPSO but the same concept has been applied on a fixed platform (Figures 32, 33).

Fig. 31 An FPSO (Floating Production, Storage & Offloading platform) for Norwegian N Sea Note Stainless Steel Fire and blast resistant escape tunnel all along the side.

In both cases one needs to allow for differential expansion between the outer carcass and the trusses during fire and to provide sliding bearings and expansion joints at interfaces between tunnel sections. These are complex as support loadings in both explosion and fire can be high.

On a fixed platform the tunnel dips down to bring the bottom level of the support cantilevers to the top level of the design air gap (flush with the soffit of the main platform deck girders).

Figure 32 shows a cross section through a Type 2 escape tunnel mounted on a fixed platform.

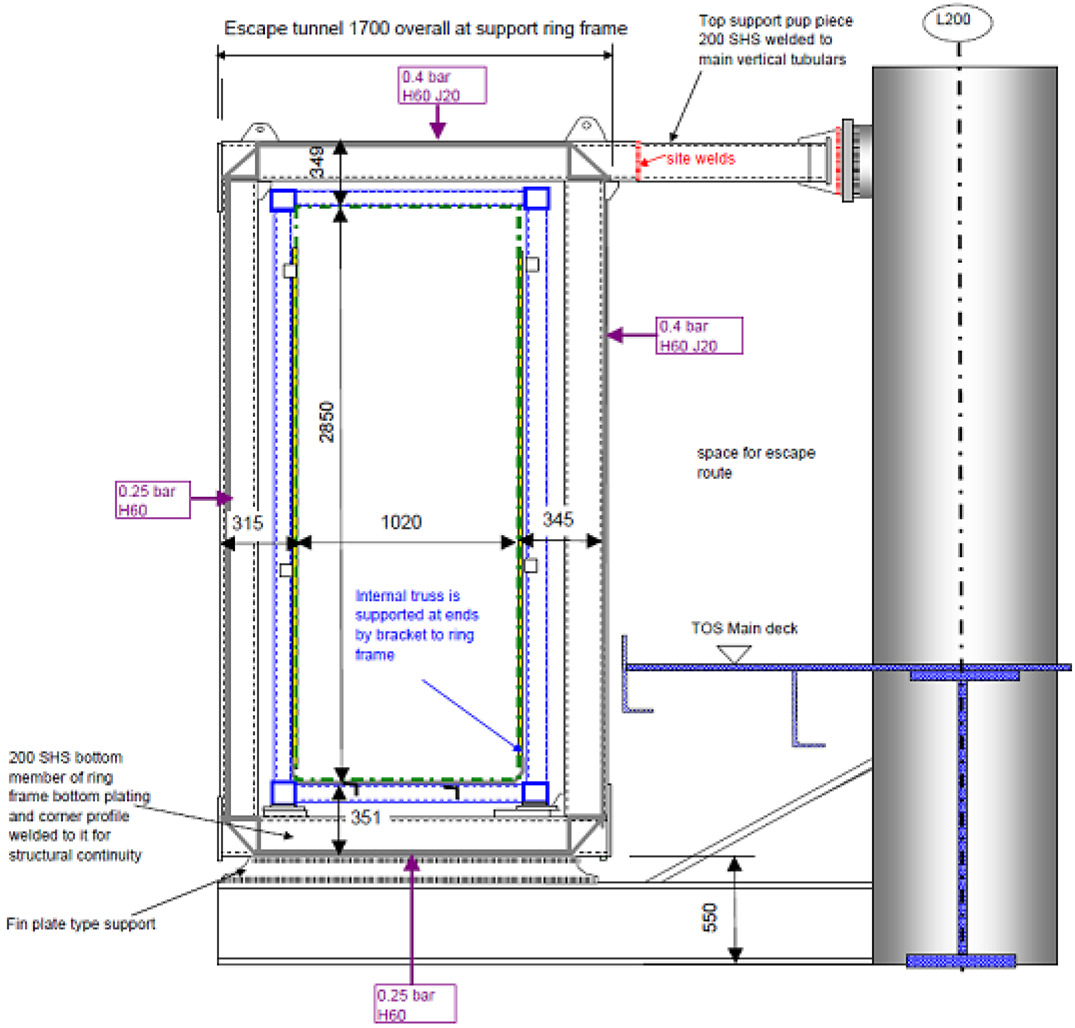


Fig. 32 Type 2 Fixed platform escape tunnel based on stressed skin design. Note additional escape route outside the tunnel. The sea is to the left of the tunnel.

The tunnel is supported on cantilever beams mounted on the platform main frame. Figure 32 shows the cross section at the support point where there is a strong ring frame made of thick wall Grade S355 RHS sections, This is bottom supported and supported laterally at the top. In Figure 32 the internal truss is shown in blue and spans simply between ring frames. The interior of the type 2 escape tunnel is much like the type 1 unit shown in Figure 30.

Figure 33 shows a tunnel carcass module about 12m long in construction at Booth Industries Ltd in Bolton.

Fig. 33 A section of a stainless steel escape tunnel carcass in construction in UK with a carbon steel support ring frame attached by welding and fire protected with intumescent PFP at site.

The stressed skin outer "box" is an all-welded duplex stainless structure with fabricated triangular box section corners or chords, vertically corrugated blastwall sides for blast and shear buckling resistance and flat stiffened plate floor and roof. Corrugated construction cannot apply here because water would pond causing corrosion risk.

Arch profile corrugated sides are used, not only for their superior blast resistance but also for their superior shear buckling resistance which is particularly relevant as thicknesses may be only 2 – 3mm.

The outer box is fully welded to the carbon steel ring frames. The tunnel is delivered ex works as fully insulated (ceramic fibre) and outfitted in lengths up to 12m, transported to platform construction yard, lifted onto the cantilevers, welded end-to-end on the platform.

The expansion joints take small fatiguing movements on an FPSO where ship flexing in waves occurs. More generally, large movements up to 150mm occur in any direction (except vertical) due to shock effects on the main structure in blast and due to differential expansion between the escape tunnel and the support structure in fire.

For design purposes, one can idealise the tunnel as a box beam and analyse it as a stick model in STAAD FE package, both for fire and explosion. For explosion the SDOF modelisation is used (see Section 6 above) and for fire one needs to ramp up the heating of the carcass in steps, analyses the curving of the carcass due to only being heated on one side and the top and including strength reduction of the stainless steel.

The corrugated sides and plated top and bottom can be analysed based on Eurocode 3 and [3]. But the dynamic interaction between all these effects can only be modelled in LSDYNA in the time domain. These models are very large, typically 600 000 elements. If a good comparison between the STAAD model and the LSDYNA model occurs not all tunnel sections need to be looked at with LSDYNA.

Stainless steel thicknesses are in the range 2 to 8mm but the sliding bearings welded to the ring frames include stainless steel components up to 100mm thick

Figure 34 shows a section of a more sophisticated type 2 escape tunnel: for the FPSO shown in Figure 31. The explosion design pressures were much higher (2 to 3.3bar) and the tunnel was wider as it included 60 control panels and electrical switchboards serving the modules outside the inboard wall of the tunnel. These could be operated from the safety of the tunnel.

Fig. 34 Section of a type 2 FPSO escape tunnel, note door to the side. This communicates with a stainless blast resistant airlock room sited on the deck of the FPSO.

Lastly it remains to be said that special fire and blast-resistant flexible seals are located at expansion joints, these are design for axial and horizontal shearing movement up to 150mm.

These are either rubber reinforced with stainless steel wire mesh or of stainless steel, like pipe bellows. They are specialist proprietary items that need specialist design and testing for fire and explosion.

8 New Possibilities 1: Retrofit Escape Towers for Residential Tower Blocks

On 14th June 2017 a catastrophic fire occurred in Grenfell tower in London. The fire commenced in a fridge in a 4th floor flat and spread up and around the face of the building leaving the cladding ablaze. The fire lasted for over 24 hours and

80 people were killed. (New Civil Engineer August and September 2017 issues)[8] covers the knowledge gained to date and the current indications of the way forward,

The government has called for a public enquiry that is likely to prove as significant and far-reaching as the Cullen enquiry into the Piper Alpha disaster.

Much attention is on the cladding issues but also of significance were comments made by the fire fighters to BBC news during the first 24hrs. Firemen went up the tower to fight fires and rescue people. Smoke was a major problem and the fact that the fire-fighters' breathing apparatus would only give them a limited time inside the building made it difficult to reach and rescue people from upper floors.

Another problem was commented on was that the fireman's progress up the stairs was inhibited by escapees coming down them and this delayed the clearance of the building.

Figure 35[9] shows the locations of the fatalities and confirmed that the largest numbers of fatalities occurred on the upper floors.

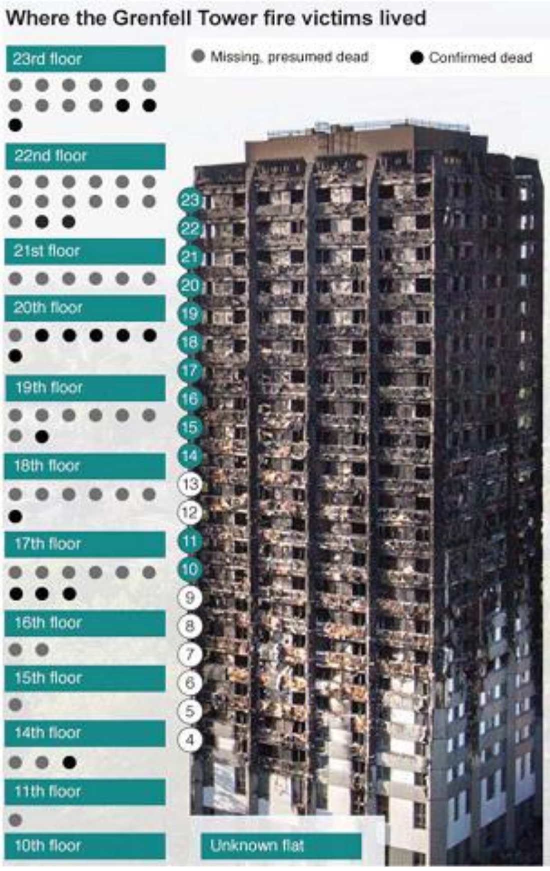


Fig. 35 Grenfell tower fire locations of fatalities.

It is therefore a purpose of this paper to present a possible means of improving access and escape by retrofitting a fire and smoke proof stair-tower to such blocks of flats. It is not unknown for such buildings to include a special fireman access stair set.

In the present paper a prefabricated stair tower is put forward, based on the type 1 offshore escape tunnel described in section 7 above. In many cases it may not prove to be practical but it may in some.

Figure 36 shows a plan on a floor with such a stair tower. Clearly there would be some loss of habitable space, not only on the floor levels where the escape routes into the tower are located but on all floors due to blockage of light. The tower could have round ends without affecting construction method and would be streamlined and then pick up lower wind load.

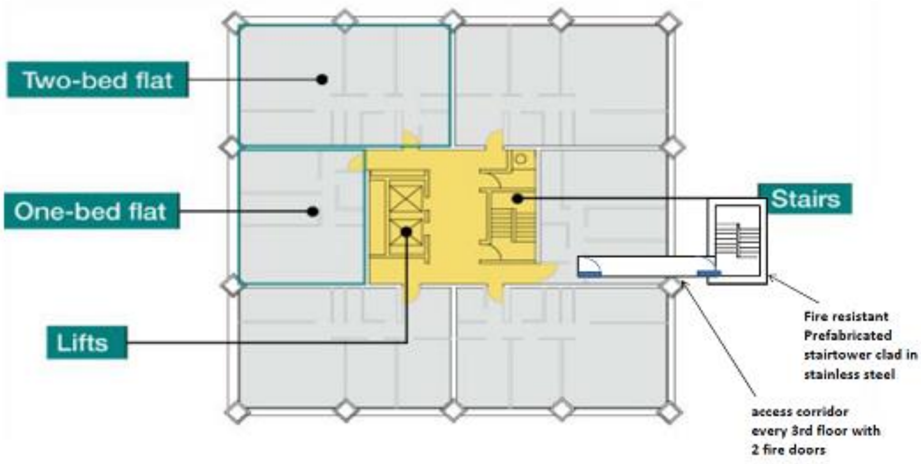


Fig. 36 Plan on building with a retrofit prefabricated stainless steel clad emergency stair tower.

The stair tower would have to have a plan area of about 5m x 3m to meet current dimensional requirements on escape stairs and door access, which means that to be transportable to location it would have to arrive in module heights of about 3-4m and be bolted together at site. The cladding would be vertical spanning corrugated stainless steel and the tower frame would be in Grade S355 and require minimum 150 or 200 SHS legs, depending upon building height and how the tower is supported for wind load. There would be internal insulation of ceramic fibre or rockwool free of phenolic binder, also a thin stainless steel liner as in Figure 30 above.

Every 10m or so there would be a horizontal seal of the type used on escape tunnels but preferably as a one piece fabricated stainless steel bellows type (single lobe). .

For optimum safety and convenience entry might best be at every 3rd floor and the tower lighting and ventilation powered from a location other than the tower block. Such a tower would be lightweight and probably weigh about 1.5T/m complete.

9 New Possibilities 2: Battery Packs for Hybrid Cars and Electric Vehicles (EVs) and Fixed Domestic Battery Systems

Current technology for EVs and some Hybrids involves the use of Lithium Ion batteries of one sort or another. This is a form of high energy density battery which has a lot of energy contained in a small volume and has fire and explosion risk.

Figure 37 shows a fire in a Tesla S at a charging station that occurred in March 2016 in Norway[10]. No one was hurt.

Fig. 37 Tesla fire at a high current charging station in Norway. Note vehicle surrounded by large amounts of foam.

The vehicle is surrounded by a sea of foam which is not extinguishing the fire.

Wikipedia looks at risks with Lithium Ion batteries. [11] states:

If overheated or overcharged, Li-ion batteries may suffer thermal runaway and cell rupture. In extreme cases this can lead to leakage, explosion or fire.

The reference also says:

Other safety features are required in each cell

- *Shut-down separator (for overheating)*
- *Tear-away tab (for internal pressure relief)*
- *Vent (pressure relief in case of severe outgassing*)

It then says:

Thermal interrupt (overcurrent/overcharging/environmental exposure) several aircraft crashes have been attributed to burning Li-Ion batteries.

NFPA advises US firefighters that when a battery pack ignites in an EV it burns for 30min to 1hr despite firefighting activity.

[12] gives guidance to firefighters coping with electric vehicle fires. It requires up to 25 tonnes of water (3 full fire tenders) to control an EV fire. Furthermore the fire can reignite in the wreck for up 24hrs after the accident so it is difficult to move the wreckage from a crash.

No mention is made in the video about coping with casualties at the same time as the protracted firefighting efforts nor about toxic fumes (they were not monitored in the tests. It is known that a significant amount of toxic smoke is given off (see also Wikipedia).

In [13]:

"an EV's energy source can be explosive when it gets into a serious enough accident," said Sullivan, an analyst with AutoPacific. "I don't know if there's an answer to the explosive nature of lithium-ion when those batteries are disturbed."

But another significant aspect of the image in Figure 37 is that almost everything above about 50cm level has collapsed. The high weight of the batteries means that the bodywork is a weight saving operation that involves the use of composites (Not only Tesla). In a conventional motor vehicle fire the passenger cage would still be intact and the wreck would still be 1.2 to 1.5m high. This has implications for persons injured in an EV crash.

It is also possible that changes in design are part due to design changes to accommodate the battery pack which is a flat chassis type structure, and smaller motors located at axis the levels of the wheels.

Clearly the form of construction of this vehicle is different from that of conventional petrol, diesel and hybrid vehicles and it could behave quite differently in some types of serious crashes.

It seems safe to conclude that if this aspect of EV design is combined with the battery pack risks and firefighting aspects, an increase in fatalities in crashes may be expected as the proportion of EVs on the roads rises.

It is quite possible that the overall incidence of battery fires/ explosions in electric vehicles is lower than it is in petrol/diesel vehicles but the problem is the incidence of fires and explosions in accidents coupled to the increased difficulties of handling them when casualties are in the vehicles may lead to higher fatality rates in major crashes

It seems that a completely new approach to vehicle safety testing and certification might be needed for EV and Hybrid vehicles.

Now what is the role of stainless steel in all this?

The Author does not know what methods of mitigation are applied to Electric Vehicle battery design and it is likely that, at the present state of development, much is kept secret for commercial reasons.

Parallels of mitigating explosions in buildings where explosives are handled show that the basic mitigation method is "minimisation", together with minimised escalation potential of explosion and fire to adjacent cells. Such layout options could be applied to battery packs on reduced scale and may be already for some designs.

As with explosive storage one cannot stop the occurrence of explosions and fires in batteries but their rarity means that there is much mileage to be had from a solution where the battery is divided into lots of small cells each with

1. Venting of internal explosion
2. Resistance to explosion effects emanating from adjacent cells "Wrap-around"
3. Fire resistance to fires in adjacent cells
4. Enhanced fire control features

Figure 38 below illustrates a possible solution.

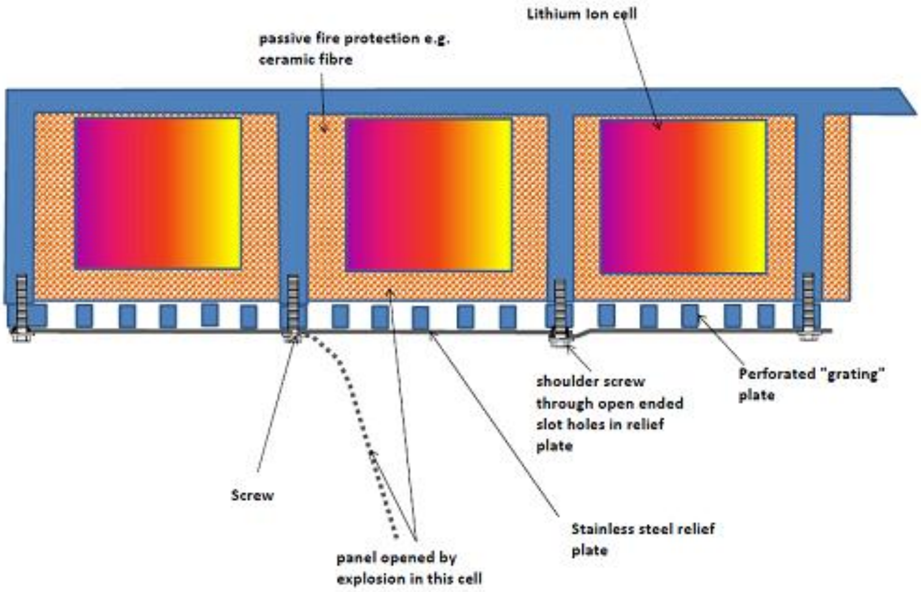


Fig. 38 A battery cell structure with in-built mitigation including stainless steel vent panels.

In Figure 38 the cell assembly is a strong compartmented box with each cell open on one face (the bottom), but covered by an open grating and a stainless steel vent panel which is ductile and resistant to external explosion (which would press it against the grating). As a fireproof covering would inhibit venting it might be best if each battery cell is contained in a fireproof package inside the box compartment. The perforated type grating, if it is under the vehicle facing downwards, would serve as protection against impact from vehicles with debris from the road, or rocks should the vehicle leave the road.

It is possible that, given the difficulty of fire-fighting when casualties are in the car, a built-in water cooling system with option of plug in to firefighting hose should be built into the vehicle at the outset. It is also to be born in mind that the car operates at high voltage and there is electrocution risk during fire-fighting, with a 220V battery system.

10 Conclusions

1. Three fire and explosion resisting products widely used in the oil and gas industry have been reviewed together with the way they are analysed in design.
2. It is shown how the unique combination of strength, corrosion resistance, ductile deformation capacity and high temperature resistance make stainless steel uniquely applicable to these applications
3. A detailed explanation of how government and industry responded to the Piper Alpha accident is included as this set the background that brought the products into use, worldwide. It consequently has implications for the two future potentially life-saving products presented.
4. The Grenfell tower fire in which 80 people died has already set in motion a process that promises to be no less far-reaching than the Piper Alpha case.
5. A possible useful stainless steel product is mooted as a means of mitigating future similar events.
6. The potential fire and explosion safety problem associated with crashes of electric vehicles fitted with Lithium Ion batteries may prove to be a source of avoidable fatalities in the long term and may benefit from a government and industry response of a similar nature to pervious generic accident incidents.
7. A way of packing the battery cells into cars with stainless steel fire resistant vent panels is mooted.

Acknowledgments

Thanks is given to Booth Industries Ltd for information on prefabricated blastwalls, GexCon for layout aspects and defining FLACS explosion loading and Arup Advanced Technology Group who have performed the NLFEA studies referred to here.

References

[1] https://en.wikipedia.org/wiki/Piper_Alpha

[2] ISO 19901-3 Petroleum and Natural Gas Industries, specific requirements for offshore structures. Part 3 Topsides Structure,

[3] Advances in the use of high strength carbon and stainless steels offshore, FABIG TM80 2014

[4] FABIG Technical Note 5 “Stainless Steel Blastwalls” published by SCI

[5] Malo K S & Ilstad H Quasistatic response of of corrugated thin wall panel.4th International conference on computational plasticity fundamentals and applications Barcelona Spain 1985

[6] FABIG Technical Note 2 "Explosion Mitigation Systems" is provided (FABIG is part of UK Steel Construction Institute)

[7] “Equipment Or Protective Systems Intended For Use In Potentially Explosive Atmospheres Directive 94/9/EC”

[8] (New Civil Engineer August and September 2017 issues)

[9] London fire: A visual guide to what happened at Grenfell Tower - BBC News 30-06-17

[10] Newspaper VG epost http://www.vg.no/forbruker/bil-baat-og-motor/elbil/tesla-brannen-kortslutning-i-bilen-men-vet-ikke-hvorfor/a/23640710/

[11] https://en.wikipedia.org/wiki/Lithium-ion_battery#Extreme_temperatures

[12] https://www.youtube.com/watch?v=mtCk3srID_w

[13] https://www.nbcnews.com/business/autos/tesla-under-fire-after-explosive-crash-n722541