How stressed is your facility?

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When we think about process safety, we tend to focus on the process related elements, such as flow, temperature, pressure etc. However, a key element that is very important is the physical structures that form part of or support the process. How stress is applied to structures or equipment can have a significant effect on the process safety outcomes. A well known process safety incident that involved a stress related failure was the Flixborough explosion, where the stresses in the temporary pipe were not considered. Another is the structural failure in the Formosa Point Comfort fire, where structural steel lacked passive fire protection, and was not able to withstand it's load in a fire scenario. Failures due to stress loading are not limited to the processing industries, for example in 1970 the West Gate Bridge in Victoria Australia collapsed during construction due to stress loads in the box girder. Similarly, in 1969 and 1970 two other box girder bridges collapsed during construction. Stress related failures can also be seen in liquid tankers that 'break their back' during loading or unloading, atmospheric storage tanks that implode on discharge due to the vacuum pressure or the in-flight break-up incidents that occurred with the de Havillland Comet. All these types of failures are related to the structural stresses, though the reason for the stress may be different. This paper will explore some case studies of stress related failures highlighting possible learnings for the processing sector in identifying and managing structural stress.

Keywords: stress, failure, learning

What is stress?

In its simplest form stress is a measure of force exerted over an area, expressed as:

$\sigma = \frac{F}{A}$ in N/m^2 where σ is stress, F is force and A is area.

There are four main static ways that force can be applied, which impacts how the stress impacts the recipient. These are tension, compression, shear and torsion, however from a dynamic perspective the force can be applied through vibrations that lead to fatigue failures. Regardless of how the force is applied, the material strength, or ability to withstand the stress is critical in safe design. Material strength can also alter depending on environmental impacts or degradation. This can include exposure to fire impacting the mechanical properties of structural steel for example. When considering a vessel, the force applied may not only be a positive pressure but can also be a negative pressure or vacuum. This paper focuses on case histories, though provides some simplified information on the nature of stress to aid understanding.

Tension, Compression, Shear and Torsion

As stated above, force can be applied in a number of ways. Tension, compression, shear and torsion are shown below in Figure 1. Tension is pulling along an axis, compression is pushing in along an axis, shear is applying opposite forces not along the same axis and torsion is twisting around an axis. Different materials react differently under the application of force. For example, typically concrete is stronger under compression but less so under tension or torsion and some steels may react better under shear or tension.

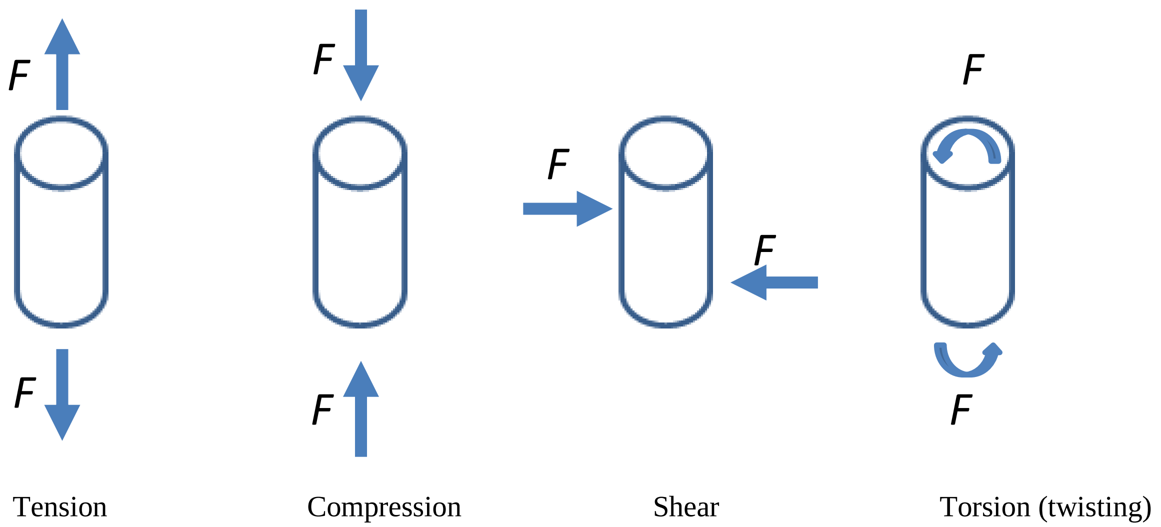

Figure 1. Forces applied for each type of stress

Material Strength

Material strength, or yield strength as it is sometimes called is the ability of the material to withstand physical deformation. The strength of the material is rated to the point at which this deformation occurs. Application of heat can impact the point at which the deformation occurs. When heat is applied to a material, such as steel, the yield point will decrease. When severe cold is applied the steel will become brittle, however prior to reaching the ductile brittle temperature transition, it will have increased yield strength. From an equipment stress point of view, it is important to ensure that structural steel where it could be impacted by fire is protected to ensure that it maintains it's strength during that fire, rather than loosing strength and collapsing. For use of metals in cryogenic situations, specific metallurgy is required to balance the brittleness against the required yield strength. It should also be noted that when steel is welded, the weld site itself is extremely strong, however the hear affected zone around the weld is a weaker point. This type of weakness needs to be taken into account when looking at a material's strength.

Vibration

Vibration is the cyclical application of force in some way. This is usually measured as a frequency on the hertz scale. When vibration is occurring in metals, the impact on yield strength may vary depending on the material and the frequency. It can be known to both increase and decrease over time. Vibration is a concern in process facilities, as there are many sources for it to occur, such as flow through pipes, changing pressures or vibration from motors. For this reason, vibration must be monitored, and modelling conducted to understand the impact that vibration may have on inducing stress related failure of equipment.

Case Histories

There are many examples of where stress has resulted in catastrophic failure of equipment or facilities. At its core, even a Boiling Liquid Expanding Vapour Explosion (BLEVE), with the force being exerted in the vessel exceeding the yield strength of the wall as the temperature weakens the material, resulting in the vessel rupturing is a stress related failure. This paper will discuss four specific stress related incidents and two generic types of failures.

Process Plants

<u>Flixborough</u>

The Flixborough disaster occurred in 1974 and is considered to be one of the most significant process safety events. The facility manufactured an intermediate product used to make nylon. The process required the oxidisation of cyclohexane, a flammable substance, through six reactors in series, connected with metal expansion bellows. These reactors were operated at high temperature and pressure (Turney, 2014). There had been a history of reactor issues, and approximately two months prior to the incident, reactor five developed cracks and needed to be taken out of service for repair. It was determined that the process could continue with one reactor removed. To facilitate this, a section of pipe was inserted where the fifth reactor would have been. Though the fittings from the reactors were 28 inch, a connecting pipe was fabricated in 20 inch pipe and installed between the two reactors. This connection was not subject to design calculations or testing prior to restarting the process. While a scaffold was used to support the pipe, it was not enough to withstand the bending moments exerted though the process operation. The plant operated in this manner for approximately two months, until the process was shut down to repair a minor leak. On start up the 20 inch temporary pipe failed, releasing tonnes of boiling cyclohexane, which subsequently ignited. The explosion was estimated to be the equivalent of between 15 and 45 tonnes of TNT. The explosion killed 28 workers, and seriously injured 89 others, both onsite and offsite. The plant was destroyed as well as approximately 2000 buildings nearby (Kerin, 2015). When the reactor was in place there were expansion bellows between it and the joining pipes. These expansion bellows absorbed the bending moments that occurred due to the cyclic nature of the reactor operation. With a reactor removed and replace by the fixed piping, the bending moments were not understood, and the pipe could not withstand the stress, eventually failing under it.

<u>Formosa Point Comfort</u>

In 2005 at the Point Comfort Olefins II unit, a trailer being towed by a fork truck collided with a small drain valve on a liquid propylene system. This resulted in a leak that formed a vapour cloud and resulted in an unconfined low-speed deflagration. While the initial triggering event of damaging the valve assembly is not strictly a stress related incident, (although the impact resulted in sufficient force being applied to damage the value) of more interest here is the impact of thermal radiation from the fire on unprotected structural steel **(CSB, 2006)**. As was stated above, radiant heat applied to structure steel lowers its yield strength, thus making it "weaker" and not able to withstand the expected stress imposed. In this incident the collapse of plant from structure steel failure increased the magnitude of the incident. Figure 2 shows how a bare steel column and a fireproofed column fared in the fire.

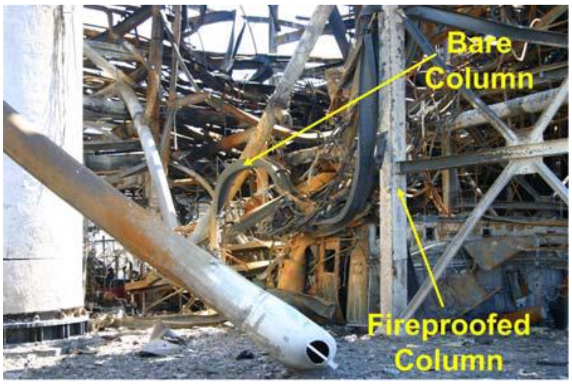

Figure 2. Difference between bare and fireproofed columns (CSB, 2006)

Non-Process

West Gate Bridge

The West Gate Bridge is a steel box girder cable-stayed construction that spans the Yarra River in Melbourne Australia. It is a length of over 2.5km and sits at a height of 58 m above the water. During construction, on 15 October 1970 a 367 ft span suddenly collapsed. Thirty-five men were killed as a result, either they were working on the bridge at the time or resting in construction huts located directly below the span. A memorial is now at this location (see Figure 3). This incident occurred four months after a similar box girder bridge collapsed in construction near Milford Haven, Wales, killing four workers. There were also three other box girder bridges that collapsed due to inappropriate stresses during construction around this time. (Engineers Ireland, 2016) Lessons were taken from the Milford Haven bridge and additional stiffening was incorporated into the West Gate construction method, however the nature of the stresses was not understood (Barber, 1971). During construction an attempt was made to correct an error in the camber of the bridge by placing several heavy weights, known as kentledges, to force the box girder into line. This application of weight caused the buckling of one of the top plates, known as a flange (see Figure 4). In an effort to correct the buckling, several bolts on the transverse splice were removed in the upper flange near the centre (see Figure 5). This caused the section to spring loose and collapse, falling to the ground below. It was determined that the bridge did not have adequate margins of safety during construction, nor would it have had adequate safety margins during operation had it been erected (Barber, 1971). When the collapse occurred several areas of the steel were torn (see Figure 6). An enquiry found that the project engineer reluctantly agreed to the use of the kentledges because he could not raise any "rational" objections. (Barber, 1971) The engineer could not prove it was unsafe, therefore it was assumed to be safe. This requirement to justify that a course of action is unsafe to prevent it occurring is a factor in other incidents, such as the launch decision for Space Shuttle Columbia (Rogers, 1986). The rocket booster engineers could not prove it was unsafe with the data they had; therefore, it was assumed to be safe. The bridge was later completed in 1978 and still stands today, though it has had a major strengthening project completed. When it was opened it was carrying 40,000 vehicles per day, and in 2006 it was carrying approximately 160,000 vehicles per day. (Upgrade, 2015)

Figure 3. Memorial to workers killed at the base of the pier where the collapse occurred and 35 stone pillars representing those lost.

Figure 4. Shows a similar buckle that developed after the kentledges were loaded

Figure 5. Shows the failure point on the flange where they had started to remove some bolts to release the stress causing the buckling. This was the failure point on the span that collapsed.

Figure 6. Section of the inner web of the box girder, shows where the steel was torn, mainly in the heat affected zones around welds.

Sea tanker failures

Sea tankers are constructed of steel plates, with internal ribs for structural stability. When a tanker is loaded or unloaded, the plates and structure are placed under a changing stress situation. Loading or unloading of a tanker, including ballasting, needs to be undertaken in a certain order to prevent hogging of the vessel. This is when a ship curves up in the centre and sags at each end and can result in a physical breaking of the hull. The hogging is usually a result of excess stress occurring in the structure and can be caused by uneven loads. For example, a ship should be unloaded from the tanks closed to the bow and then work back, this will result in the bow rising from the water. If the tanks in the middle of ship are unloaded first, these tanks will be more buoyant and try to rise in the water, but with the weight remaining the same in the bow and at the stern (with the engine weight) the centre is forced up with either end pulling down. This follows the principle of Euler-Bernoulli beam theory. Refer to Figure 7 showing a tanker with a broken back from hogging.

Figure 7. Tanker with broken back from hogging (Munro, 2017)

Atmospheric storage tank failures

In a similar manner to sea tankers, there is an assumption that because the vessel is constructed from steel, it must be strong. This assumption has been proved wrong time and again as we see items as simple as a plastic bag over a vent or a blocked flame arrestor on an atmospheric tank result in the sucking in of the tank when a slight vacuum is applied. Most atmospheric storage tanks may be able to withstand a positive pressure of around 2kPa, but can only withstand a vacuum of approximately 0.6 kPa (Kletz, 1999). This equates to a water column of approximately 6cm only. The application of a small amount of stress on the tank can result in its catastrophic failure. Refer Figure 8 showing a tank that has been sucked in.

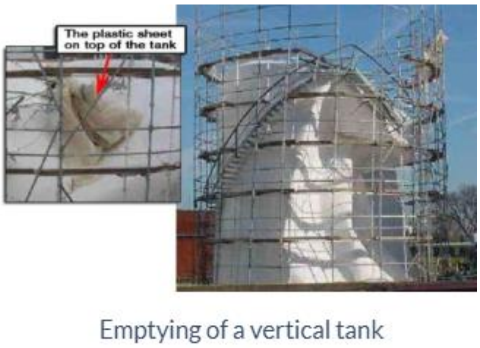

Figure 8. Vertical storage tank sucked in (QAQC Construction, 2019)

de Havilland Comet

In the mid-20th century the de Havilland Comet entered service as a commercial jet liner. It used turbojet engines rather than propeller driven and could therefore cruise at higher altitudes. This resulted in the need for the cabin to be pressurised. The cabin also had large rectangular windows for the passengers to see out. In January 1954 a Comet took off from Rome and soon after disintegrated, killing all 29 passengers and six crew. While this saw the grounding of the plane for a brief period, the exact cause was not determined. After some modifications, the plane was again released into service. In early April of the same year, a second plane exploded in mid-air. A series of investigations undertaken at Royal Aircraft Establishment Farnborough determined two key causes for this mid-air explosion. Firstly, the skin of the plane was as thin as possible to reduce weight, and this was under cycling stress from the internal pressurisation. Secondly the corners of large rectangular windows provided a location for fatigue related cracks to start and propagate. Testing to identify the causes was conducted by submerging a plane in a large tank of water and subjecting it to stress and pressure tests. When the plane had experienced the equivalent of more than 9,000 flying hours a fatigue related crack started at the corner of one of the windows and the fuselage failed, thus identifying the failure mechanism (Hollingham, 2017).

These failures not only led to vital design changes to commercial aircraft, such as plane windows having rounded corners, but also a shift from a design philosophy of SAFE-LIFE to FAIL-SAFE. SAFE-LIFE meant that a structure was designed to operate through the anticipated fatigue life cycle without damage. This would suggest that the life of a structure would be quite short to ensure that there was no fatigue damage. FAIL-SAFE assumes all material contain initial defects and therefore may propagate during fatigue loading. Therefore, the structure needs to be designed to sustain damage without suffering failure that could be detected by inspection (Groh, 2012).

Key Learnings

If we consider Flixborough, there was no assessment of the impact of removing the expansion bellows and reactor and replacing it with a fixed pipe of smaller diameter. There were no engineers on site that understood stress, therefore the decision was made without taking the stress into account.

Considering Formosa Point Comfort, some parts of structural steel had been fire proofed but others had not. It is unclear why this had occurred, though it may be reasonable to question if there was a fundamental understanding of the risk of fire relative to the location of the structural members. Without adequate assessment by competent people, correct decisions, in this instance on fire proofing, were not be made.

The West Gate Bridge suffered from a lack of understanding of the forces not only during construction but also during operation. Cable-stayed steel box girder bridges were relatively new at this time, and there were a number of failures around the world. The errors made in this instance stem back to the engineers not being able to prove something was unsafe, when they should have turned their efforts to proving it was safe.

Looking at both sea tankers and atmospheric storage tanks, there is often an assumption that they are very strong because the steel used is so thick, however when the object made from the steel is so large, they become very fragile. Small forces exerted in the wrong place or wrong way can result in catastrophic failure of a large object. When the stressing occurs regularly such as loading and unloading of the vessels, the cyclic impact of stress much be understood as well. All people operating this type of equipment need to understand this fragility.

The de Havilland Comet exposed a new impact of cyclic stress through the pressurisation and depressurisation of the aircraft body. Importantly it shifted thinking from the concept of designing equipment for a defined safe life to designing equipment to fail in as safe a mechanism as possible.

In each case shown here the nature and or magnitude of the stresses were not understood by those involved. It is not possible to say the stresses were not understood, as in some instances they were well established scientific principles. So, it seems that an issue here is a lack of learning from previous incidents as well as a general lack of understanding of how stress impacts equipment by those in control. This highlights the importance of engaging a cross disciplinary team in design work to ensure that the team as a whole understand the hazards involved.

In complex systems, we need to apply a multi-disciplined approach, with chemical, mechanical, electrical and structural/civil engineers needed to address all aspects of a design. Once this is done the basis of design needs to be documented and the knowledge then transferred via training to the people operating.

References

Barber, E. H. (1971). *Report of the Royal Commission into the Failure of the West Gate Bridge.* Melbourne: Government Printer.

CSB. (2006). *Formosa Point Comfort Case Study.* Washington DC: CSB.

Engineers Ireland. (2016, November 01). West Gate Bridge collapse – the story of the box-girder bridge. *Engineers Journal*. Retrieved from http://www.engineersjournal.ie/2016/11/01/west-gate-bridge-collapse/

Groh, R. (2012). *The DeHavilland Comet Crash.* Bristol: Aerosapce Engineering. Retrieved November 19, 2019, from https://aerospaceengineeringblog.com/dehavilland-comet-crash/

Hollingham, R. (2017). *The British airliner that changed the world.* London: BBC. Retrieved November 19, 2019, from https://www.bbc.com/future/article/20170404-the-british-airliner-that-changed-the-world

Kerin, T. (2015). The evolution of process safety standards and legislation following landmark events. *Hazards 25.* Edinburgh: Institution of Chemical Engineers.

Kletz, T. (1999). *What went wrong?* (4 ed.). Houston: Gulf Professional Publishing.

Munro, K. (2017, December 13). Sinking bulk carrier ships by hacking HSMS. *Maritime Cyber Secuirty*. Retrieved November 19, 2019, from https://www.pentestpartners.com/security-blog/sinking-bulk-carrier-ships-by-hacking-hsms/

QAQC Construction. (2019). Pipin Hydrostatic testing. Retrieved November 19, 2019, from https://qaqc-construction.com/qaqc-systems/piping-hydrostatic-testing-overview/

Rogers, W. (1986). *Report to the President by the Presedential Commission on the Space Shuttle Challanger Accident.* Washington D.C.: NASA.

Turney, R. (2014). Flixborough: Lessons which are still relevent today. *Loss Prevention Bulletin*(237), 21-26.

Upgrade, M.-C.-W. G. (2015). *West Gate Bridge Strengthening Project.* Sydney: Australian Construction Achievement Award. Retrieved Dec 16, 2019, from https://www.acaa.net.au/wp-content/uploads/2015/05/WEST-GATE-BRIDGE-STRENGTHENING-PROJECT.pdf