Australian Compliance Laboratory

Specialising in performance testing of dangerous goods packaging

The science of drop testing plastic drums that contain liquids

This article includes an introduction to drop testing, an analysis what happens during impact, theory of impact energy and the contributing factors that lead to product failures, the behaviour of crack propagation, and common failure modes.

Abstract

This brief has been written with regard to plastic containers for the transportation of liquid dangerous goods. Furthermore, we want to give products the best chance of passing the drop test by providing an educational resource to the public.

Dangerous goods containers most commonly fail their performance requirements during the drop test. This is undesirable; however, it can be avoided with good packaging design and manufacturing technique.

For the drop test, the container is conditioned to below -18°C and then dropped onto a flat immovable surface. At the moment of impact, stresses begin to act on the container. The product will crack and fail when the sum of these stresses exceeds the strength of the material. For drop testing, these acting stresses include:

1. the applied stress, caused by impact;
2. the hydraulic stress, caused by deceleration of liquid contents;
3. and the residual stress, caused by manufacturing.

To improve the container's chance of passing the drop test, we must reduce the stress acting on it during impact. To reduce stress acting on a container during impact, consider the below recommendations.

Design recommendations

- Avoid sharp corners; only use rounded corners (fillets) with a maximum radius;
- Avoid sharp transitions in material thickness;
- Lower the stiffness of the material in areas where the stress may concentrate;
- Use a plastic that maintains some flexibility below -18°C;
- Use larger closures to distribute the stress;
- Avoid making the material too thick as it can be too rigid;
- Reduce the designed ullage volume to reduce the test mass; and
- Increase the impact time by considering the container's design.

Manufacturing recommendations

- Ensure good welds along the mould parting lines;
- Avoid internal notches or defects at the neck finish that form during processing; and
- Prevent residual stresses in the cooling stage of manufacturing.

Contents

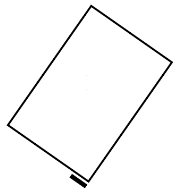
Introduction

The drop testing method described in this brief refers to the model regulations of the United Nations Recommendations on the Transport of Dangerous Goods, Revision 20, Clause 6.1.5.3. Refer to Appendix A for the full method. The Australian Code for the Transport of Dangerous Goods by Road and Rail, Edition 7.6 is derived from the model regulations.

Plastic containers containing liquids have been selected for this brief since they make up the largest portion of the dangerous goods packaging market. However, the same principles can be applied to other packaging types, materials, and drop test methods.

Drop testing

For the drop test, containers are filled to at least 98% of their maximum capacity with antifreeze, conditioned to below -18°C, orientated as illustrated below, and then lifted to the drop height.



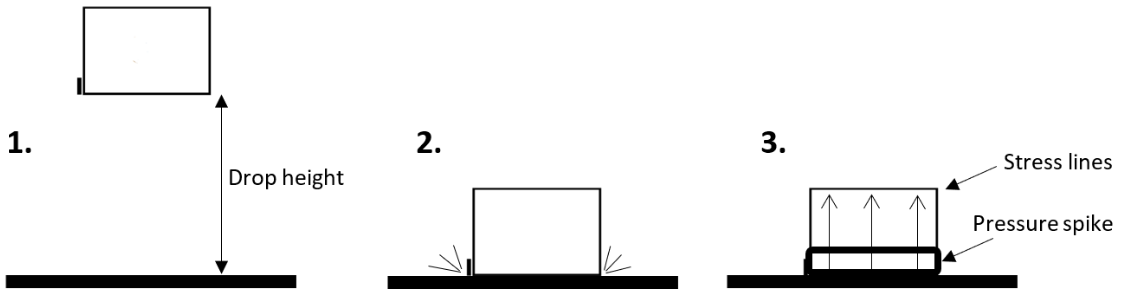
Orientation 1

Diagonally, with centre of mass directly above the top edge, adjacent to the major closure, so as the closure and seam strike the target

Orientation 6

Horizontally, so as to strike the target in the side of the drum with the major closure at the lowest point

They are then allowed to free fall and impact onto a flat, immovable surface. The process of the impact is illustrated below.



1. The container is dropped from the drop height and allowed to free-fall.
2. At the instant of impact, the impact force is being applied over the impact area as stress. The area of fluid closest to the impact point is instantly brought to rest.
3. Impact energy is absorbed by the container and its contents within a very short time. The stress runs through the body of the container to strain and yield the plastic. The fluid near the impact point is pressurised and travels as a wave away from the impact point. Simultaneously, the change in pressure compresses the air inside the container. The pressure wave reverberates throughout the container.

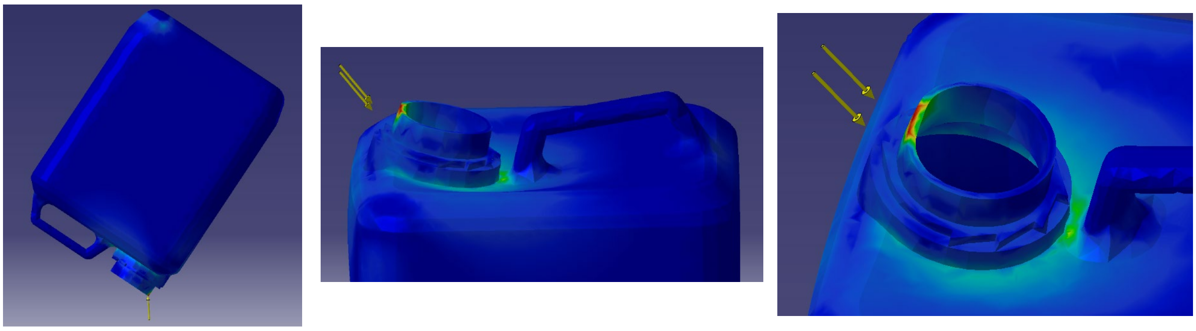
Containers fail at their weakest regions during the pressure spike caused by impact.

Drop test simulations

The below drop test simulations show us how the stress is distributed throughout the container in different drop orientations.

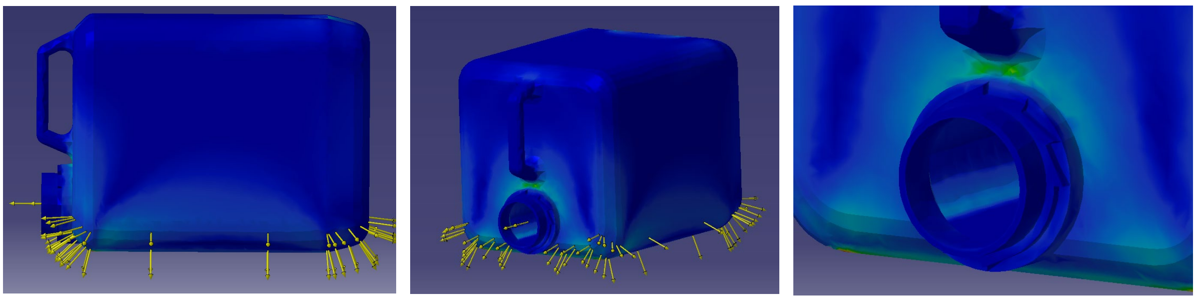
For orientation 1 below, we can see that the stress concentrates around the inner shoulder of the neck finish; particularly between the neck finish and the lifting handle. We can also see that that the container tries to absorb the impact by deforming the top inwardly. Thus, the area between the neck finish and lifting handle is pinched and a tensile force on the inside of the material is generated. This tensile force tries to rip open the container causing it to fail.

Thus, the area that requires the most reinforcement and relief is about the inner shoulder of the neck finish.



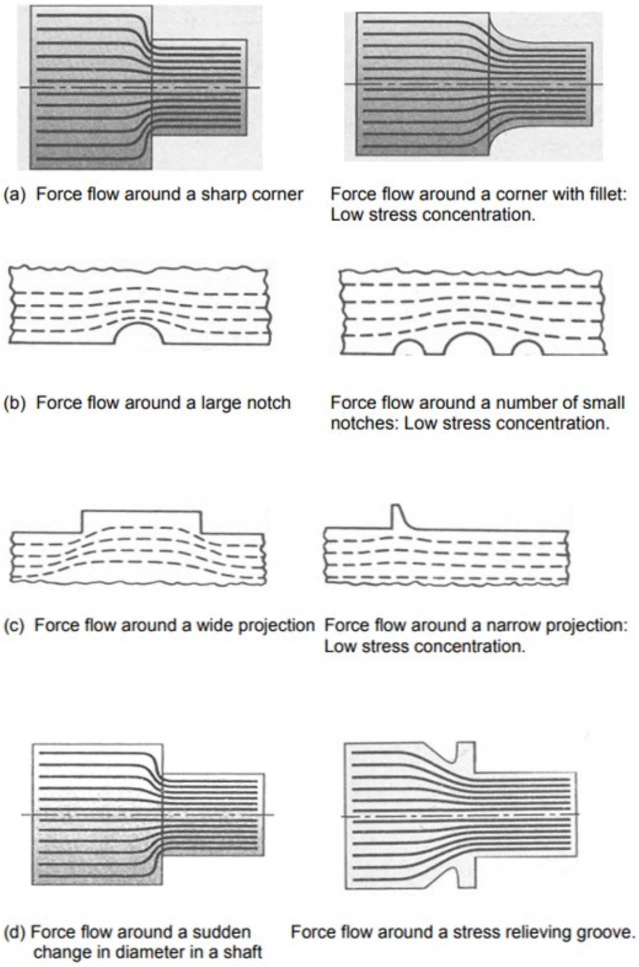
For orientation 6 below, we can see that stress similarly concentrates around the base of the container and the inner shoulder of the neck finish; particularly between the neck finish and the lifting handle. We can also see that the container tries to absorb the impact by deforming the impact zone outwardly.

Thus, the area that requires the most reinforcement and relief is about the inner shoulder of the neck finish.



Applied stress

Stress is a measure of the internal forces within an object. Typically, stress exists when a load is exerted on the object. Consider the below examples of a material being stretched axially, whereby the stress is visualised with streamlines.



(a) Force flow around a sharp corner; Force flow around a corner with fillet: Low stress concentration.

(b) Force flow around a large notch; Force flow around a number of small notches: Low stress concentration.

(c) Force flow around a wide projection; Force flow around a narrow projection: Low stress concentration.

(d) Force flow around a sudden change in diameter in a shaft; Force flow around a stress relieving groove.

When a container is dropped and it impacts the test surface, the impact force is applied over the impact area. This is referred to as the applied stress and is expressed by the equation below.

$$\sigma_{applied\ stress} = \frac{F_{impact\ force}}{A_{cross\ sectional\ area}}$$

Whereby:

$$F_{impact\ force} = m_{container\ mass} \times a_{change\ in\ the\ container's\ acceleration\ due\ to\ impact}$$

From these equations, we can deduce that:

1. $\downarrow \sigma_{applied\ stress}$ as the impact area increases, and
2. $\downarrow \sigma_{applied\ stress}$ as the impact force is decreased.

Applied force

Applied force is a direct measure of the impact experienced by the container. It's given by the classic F=ma equation expressed below.

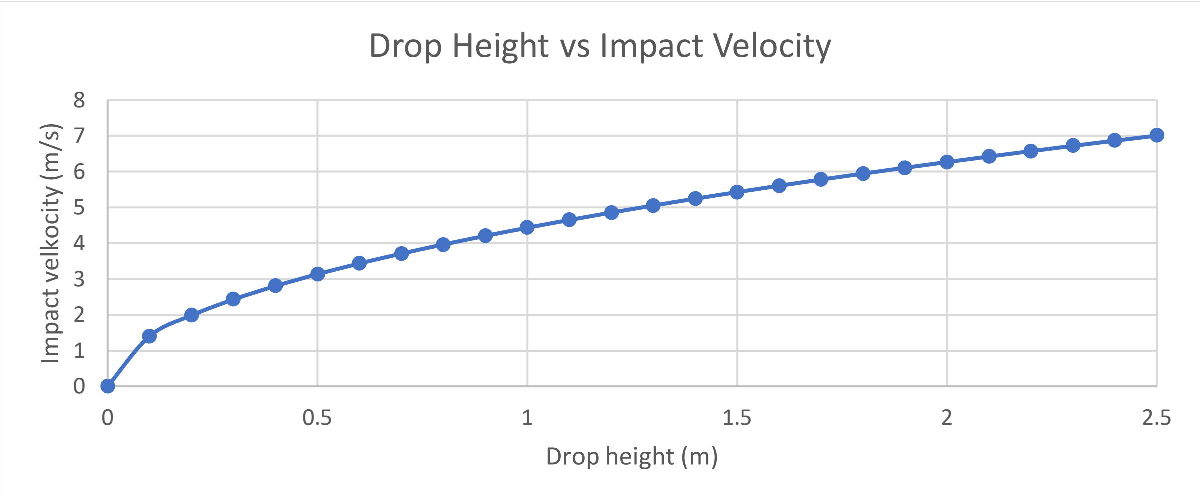
$$F_{impact\ force} = m_{container\ mass} \times a_{change\ in\ the\ container's\ acceleration\ due\ to\ impact}$$

$$F = ma = \frac{m\Delta v}{\Delta t}$$

Whereby Δv is the change in the container's velocity and Δt is the time taken to make the change. The containers velocity is a major contributor to the impact force and is given by the equation below.

$$v = \sqrt{2gH}$$

Whereby g is the container's acceleration due to gravity and H is the drop height. Since this relationship between the container's impact velocity and its drop height below. We can see that, as the drop height is increased, the change (gradient) in velocity decreases.



Impulse (change in momentum) is the measure of the container's deceleration. It can be expressed in Gs, whereby 1G = 1 multiple of earth's gravity (9.81m/s²). A container's fragility can be expressed in terms of Gs, whereby the higher the Gs, the more resilient the product. Impulse is calculated using the equation below.

$$J_{\Delta momentum} = m\Delta v$$

Using our original equations, it can be said that impulse as a factor of the applied force in the equation below.

$$J_{\Delta momentum} = F_{impact\ force} \times \Delta t$$

From these equations, we can deduce that:

1. $\downarrow F_{impact\ force}$ as we reduce the container's mass by reducing the container's maximum capacity;
2. $\downarrow F_{impact\ force}$ as we reduce the drop height by reducing the container's rating; and
3. $\downarrow F_{impact\ force}$ as we increase the impact time by considering the container's design.

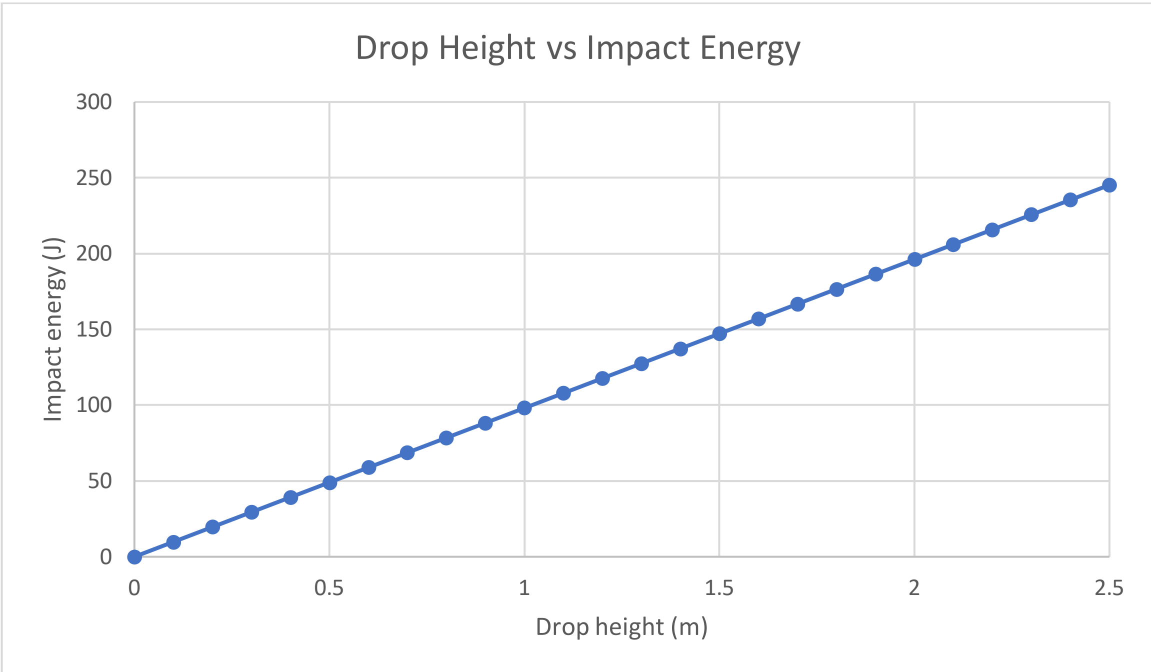
Impact energy

Impact energy can be referred to as kinetic (dynamic) energy. It is generated as the container is dropped and its speed increases. It's this kinetic energy that must be dissipated by the container upon impact. On the other hand, there is potential (unconverted) energy which increases as the container is lifted to the drop height.

When the potential energy is maximum the kinetic energy is minimum. Visa versa, when kinetic energy is maximum the potential energy is minimum. Their equations are given below.

$$E_{Kinetic_{Maximum}} = E_{Potential_{Maximum}}$$
$$\frac{1}{2} m v_{max}{}^{2} = m g H_{max}$$

From these equations it can be said that the container's impact energy increases linearly with height. The below graph is modelled for a 10kg container.



Mass-spring model

The mass-spring drop testing model assumes that the entire container acts as a homogenous spring when it absorbs the impact energy. This isn't appropriate to packagings with liquid contents since they behave with a pressure wave, thus we won't discuss the theory in detail. It is useful however for containers with solid contents. The standard spring equation is given below.

$$F_{Restoring\ force} = -k_{stiffness\ factor} \times \Delta x_{amount\ of\ extension}$$

Hydrostatic (water-hammer) stress

Upon impact, there is a sudden change in momentum of the liquid within the container which causes a localised pressure spike. This behaviour is similar to water-hammer; but only during the initial impact.

The pressure spike travels as a wave, outward from the impact point. For a container dropped flat on its side, the pressure wave will try and blow out the top and bottom of the container, often cracking the mould parting lines or the sharp corners.

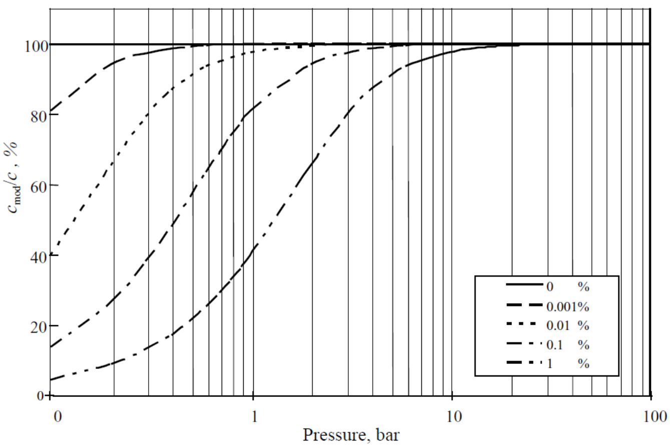
The pressure magnitude of the wave can be calculated using the equation below; whereby ρ is the density of the antifreeze, c is the pressure wave velocity, and Δv is the change in antifreeze velocity caused by impact.

$$\Delta P_{water\ hammer} = \rho \times c \times \Delta v$$

From this equation, it can be said that:

1. $\downarrow \Delta P_{water\ hammer}$ as we decrease the viscosity of the antifreeze by diluting it with water;
2. $\downarrow \Delta P_{water\ hammer}$ as we decrease the wave speed by introducing air into the system;
3. $\downarrow \Delta P_{water\ hammer}$ as we decrease the impact velocity by reducing the drop height; and
4. $\downarrow \Delta P_{water\ hammer}$ as we increase the impact time by changing the container's design.

By introducing a very small amount of air into the container fluid, we can significantly reduce the pressure magnitude. From the graph below, we can see that, for water with 1% air, the wave speed achieves only 5% of that in pure water. At higher pressure the air stiffness is increased and the effect of air presence can be neglected. This will proportionally decrease the pressure magnitude.



Furthermore, during drop testing, the pressure spike can be reduced if the containers are sealed before they are chilled. The chilling constricts the air and creates a negative pressure which the spike must overcome.

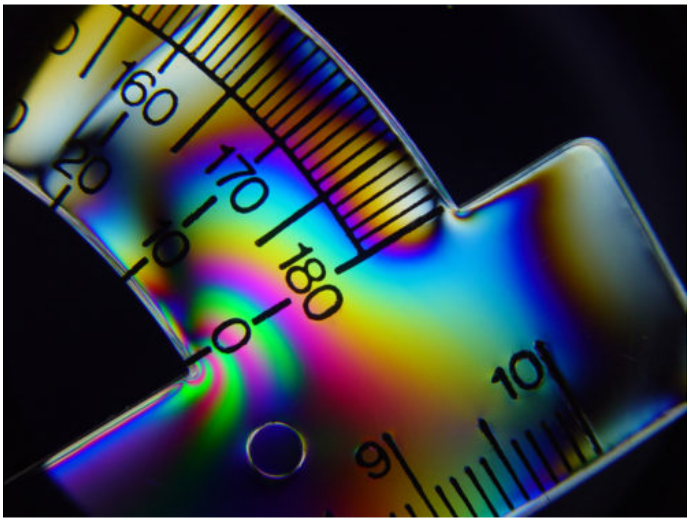
The container's shape significantly affects the pressure produced by the impact. If the container deforms upon impact, the liquid contents inside the container gradually stops, thus reducing the pressure magnitude.

For more information on the behaviour of water-hammer, refer to Appendix B.

Residual stress

Residual stress isn't a very large concern; however, it is worth consideration.

Residual stress refers to the pre-existing internal stresses within an object, and all moulded plastics have some of it. They are normally formed in moulded plastics as they are cooled, and they preload the container with directional stresses. Residual stress raisers exist in the usual culprits such as sharp corners and the tips of notches. These raisers can cause localised yielding of the plastic, therefore encouraging crack initiation, encouraging crack propagation, lowering impact strength, and cause the product to fail prematurely. In the plastic component below, polarised light shows us the stress raiser in one of the component's sharp corners.



When plastic is heated, a polymer's helix untangles and stretches out. As it's cooled, it tries to recover its initial shape. When the cooling is fast, the polymers don't have time to recover their original shape and so they are frozen in a state of stress. Therefore, the faster the cooling, the higher the internal stresses.

To avoid residual stresses, plastics should be cooled slowly and uniformly. This can be difficult to achieve since the container's outer walls cool first against the mould; and plastic is not a good thermal conductor. For these reasons, thick plastic profiles will cool unevenly and so the outer surfaces contain more residual stress than the inside of the wall.

On the topic of wall thickness, it's worth noting that thin sections will cool faster and shrink differently to that of thick sections. When there's an abrupt difference in wall thickness, there will be high residual stresses at the junction.

You can check for residual stress via environmental stress crack analysis testing or by thinly cutting the sample and watching its deformation over time.

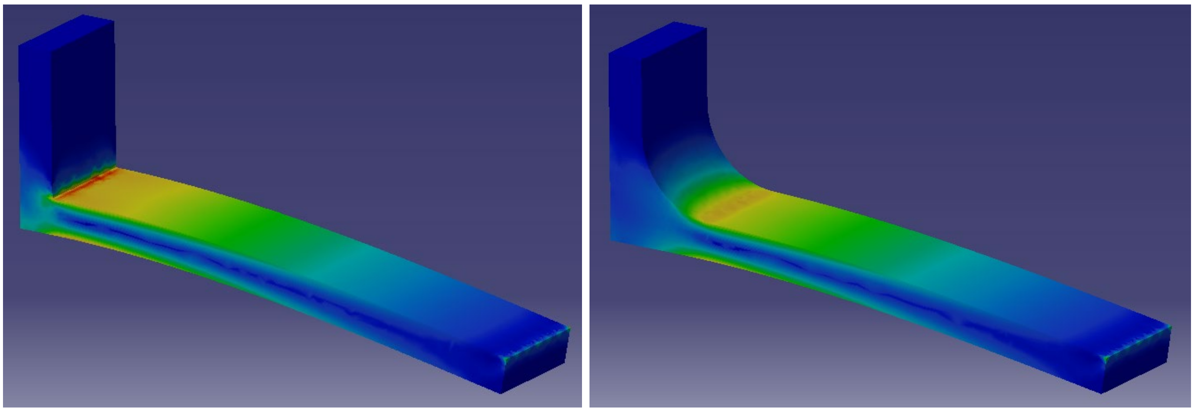
Stress raisers

A stress raiser ("stress concentration" or "stress riser") is a location within an object where the stress is concentrated. These concentrations have a larger stress within the object when compared to the applied stress that is exerted on the object. Maximum stress from the concentration can be calculated as:

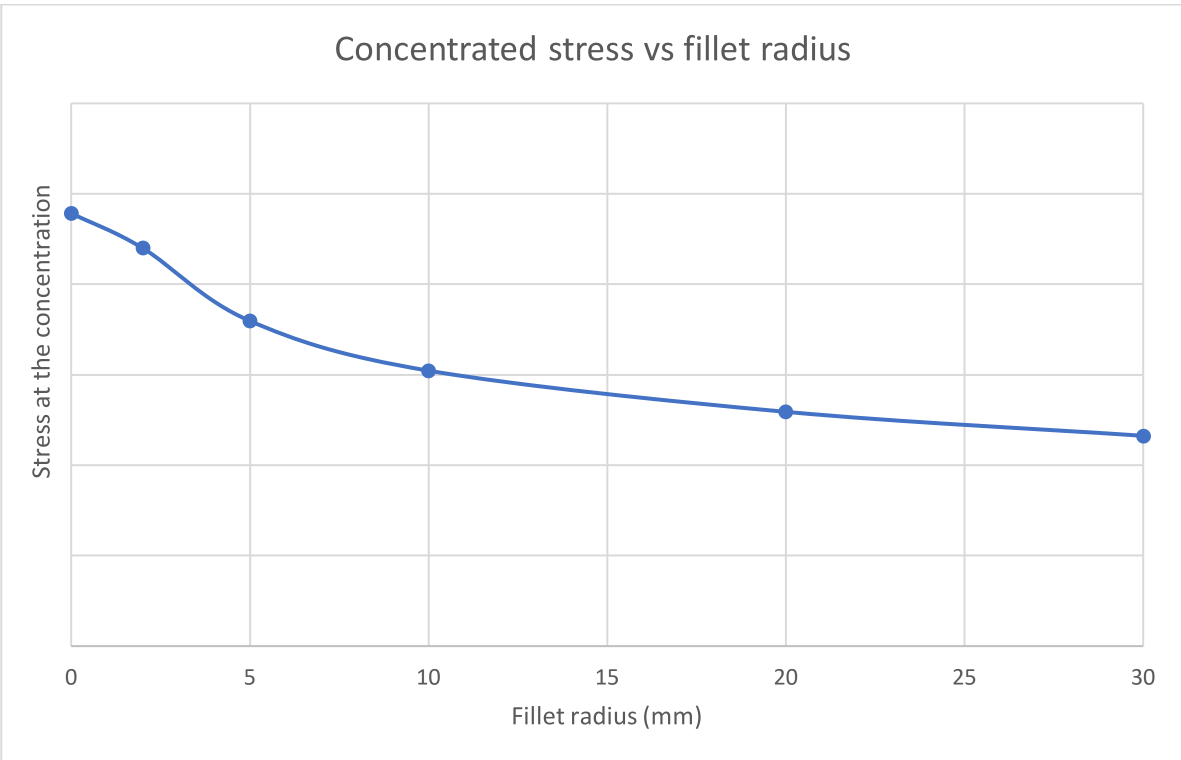
$$\sigma_{maximum\ stress} = \sigma_{applied\ stress} \times K_{stress\ concenration\ factor}$$

Sharp corners

A sharp corner acts as a stress raiser. This is because it's difficult for the stress to transfer through the material smoothly. To reduce the stress, replace sharp corners with a large fillet as shown below. The higher the fillet radius, the lower the stress concentration.

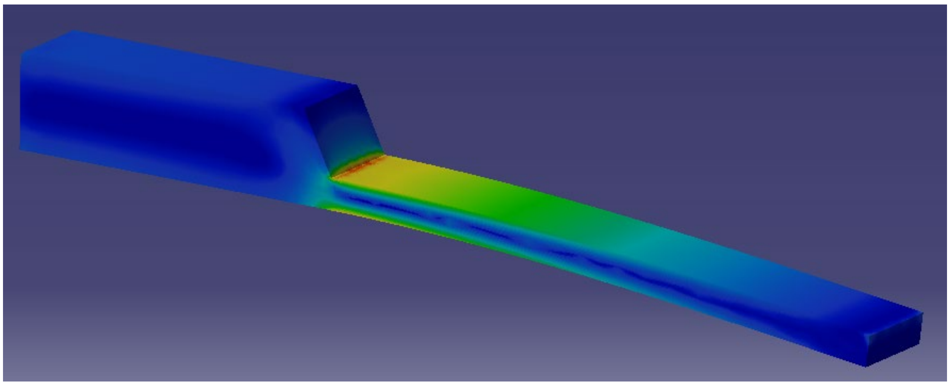


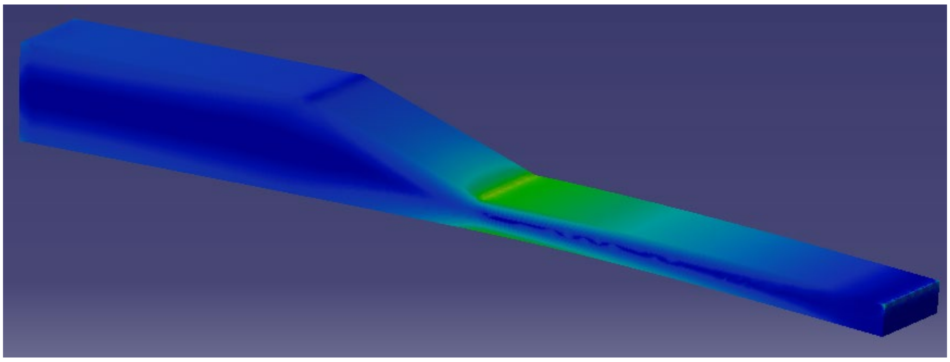
We can see the significance adding a radius from the below graph.



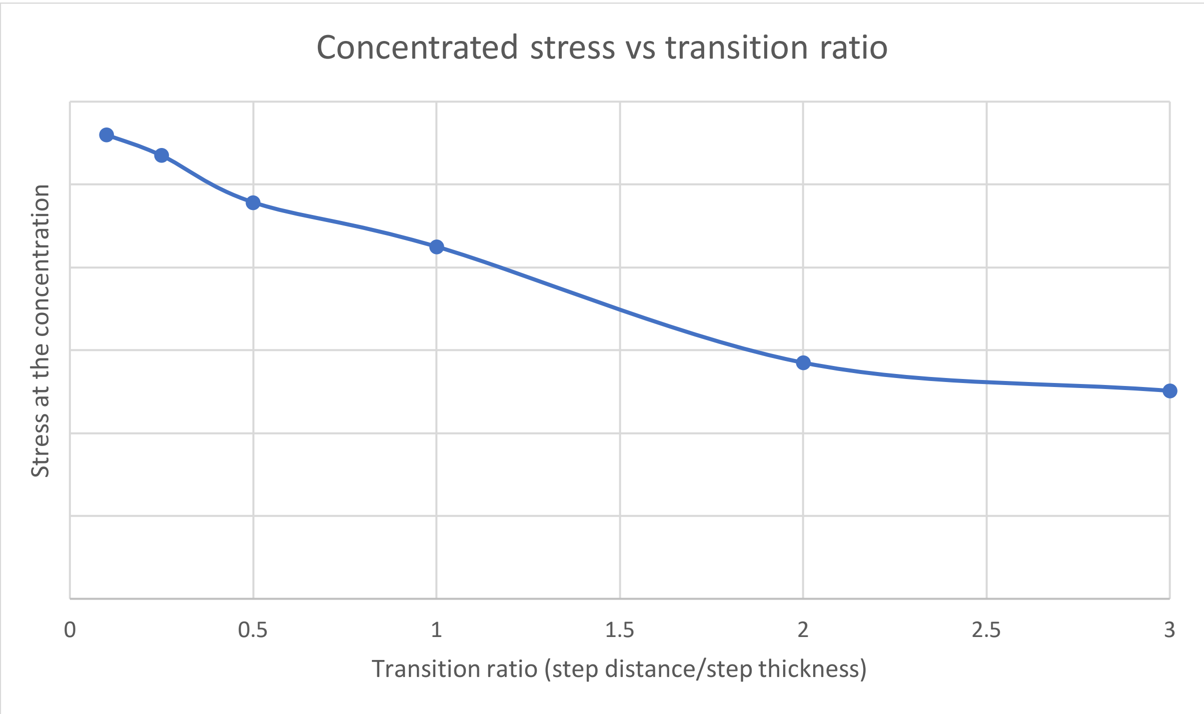
Sharp changes in wall thickness

A sharp change in wall thickness (cross-sectional area) acts as a stress raiser. Similarly, this is because it's difficult for the stress to transfer through the material smoothly. Furthermore, the stiffness mismatch will drive the stress raiser higher. To reduce stress, ensure uniform wall thickness or slow transitions as shown below. The longer the transition, the lower the stress concentration.



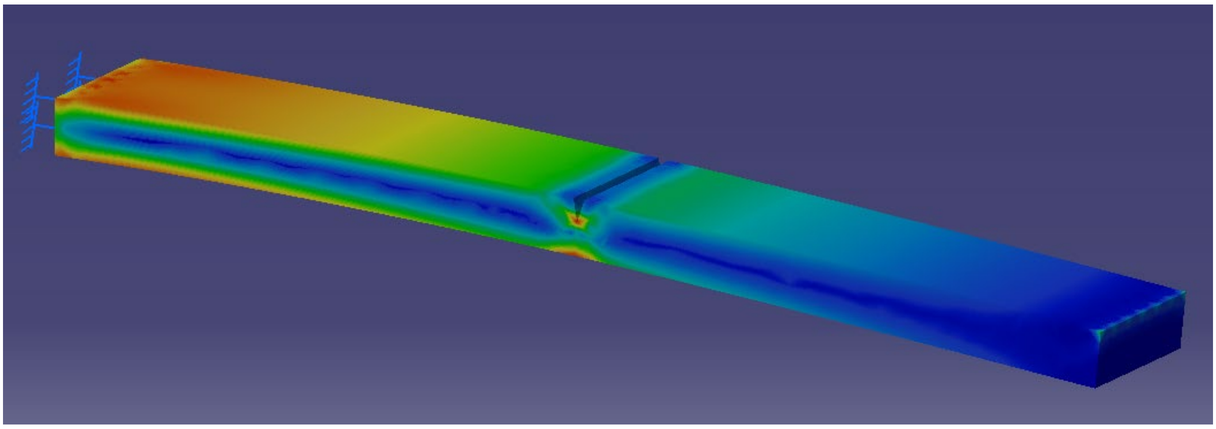


We can see the significance adding a increasing the transition ratio from the below graph.



Cracks

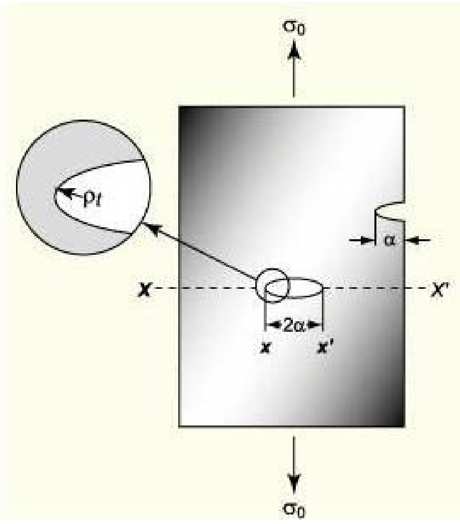
Flaws at the surface or flaws within a material act as cracks. Stress cannot be transferred through a crack and so a concentration forms at its tip. When these concentrations exceed the material's yield stress, it will plastically deform and the crack will increase in size. These flaws act as sites of crack propagation.



Calculating the stress raiser

For a crack, the stress raiser can be calculated using the equation below; whereby *a* is the length of the crack, and θ is the radius of the crack tip.

$$K_{stress\ concenration\ factor} = \left(1 + 2\sqrt{\frac{a}{\theta}}\right)$$



Using this equation, it can be said that:

1. $K_{stress\ concenration\ factor}$ is a product of a crack's geometry rather than its size;
2. $\downarrow K_{stress\ concenration\ factor}$ with shallower cracks;
3. $\downarrow K_{stress\ concenration\ factor}$ with more blunt cracks; and
4. As θ approaches zero, the stress theoretically increases to infinite. Practically however, this doesn't occur since the material will yield and plastically deform.

Fracture toughness for sharp cracks

For sharp cracks, fracture toughness is when a crack's propagation becomes fast and uncontrolled. The limit of when this will occur can be calculated using the equation below; whereby G_c is the critical energy required for fracture, a is the crack length, and E is the materials modulus of elasticity.

$$G_{critical} = \frac{{\sigma_{applied\ stress}}^2 \times \pi \times a}{E}$$

$$K_{critical_{stress\ concentration\ factor}} = \sqrt{G_{critical} \times E}$$

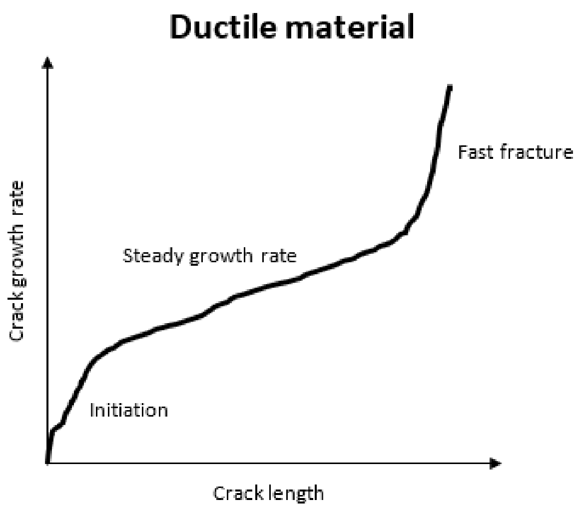
$$K_{critical_{stress\ concentration\ factor}} = \sigma_{applied\ stress} \times \sqrt{\pi \times a}$$

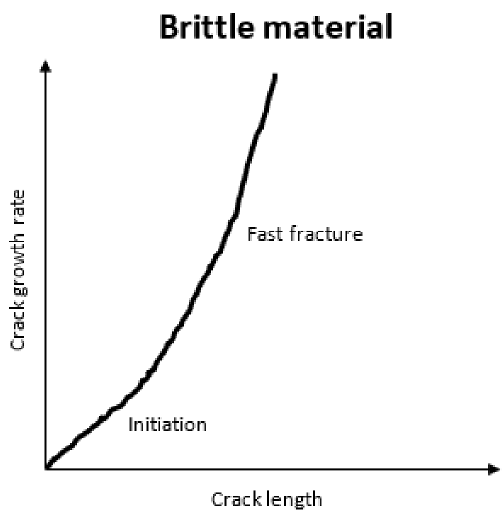
Using these equations, it can be said that:

1. $G_{critical}$ is proportional to the crack length;
2. $\downarrow G_{critical}$ by using a more flexible material. A plastic's modulus cannot be changed however a jerrycan's wall thickness can be decreased to improve flexibility. Thicker walls can introduce material constraint and reduce resistance to fast fracture.
3. $\downarrow K_{critical_{stress\ concentration\ factor}}$ by using a more flexible material; and
4. $\downarrow K_{critical_{stress\ concentration\ factor}}$ by ensuring that, if there are cracks, they are very short.

Crack propagation

Cracks propagate in three stages: Initiation, steady growth, and rapid growth.





1st stage, initiation

Impact occurs and the stress concentration exceeds the material's yield stress causing it to plastically deform. This has a crazing (whitening) effect on the plastic as it yields and creates micro-voids. If the stress is high enough, the micro-voids coalesce and the crack forms.

2nd stage, steady growth

In this stage, the crack continues to grow by plastically tearing through the material. However, if the crack grows too long, then the stress concentration becomes too high and the growth rate becomes unstable. The remaining impact energy goes into rapidly growing the crack.

Since drop tests on plastic containers are conducted at below -18°C, the plastic becomes brittle and so the second stage is normally so small that it can be neglected. Therefore, the crack can rapidly grow immediately after initiation. Although the yield strength of the material is higher, the ability for the material to move is decreased and so its fracture toughness is low.

In the laboratory, generally no steady state growth is observed in failures except in small regions around the crack and at its end tip.

3rd stage, rapid growth

Generally, once the third stage is reached, the crack will grow without needing more energy. The crack is now large enough that the material cannot support the stress and so it undergoes fast fracture. When this happens, the propagating crack is not crazing the plastic but rather it's cleaving its way between the grain structure. However, a crack will stop growing if it propagates to an area of lower stress (whereby it goes back to crazing) or to an area where the geometry that is able to bear the stress.

Common manufacturing issues

Behaviour	Effect	Remedy
Random cracking of the body material. The plastic is too brittle or high residual stress.	This reduces fracture strain, reduces fracture toughness, increases crack propagation rate, reduces the ability to absorb impact energy	Reduce the parison temperature, reduce the amount of regrind or recycled material, slow down the mould cooling cycle
The mould parting line cracks. Poor welds.	This notch is a large stress concentration in the area where most of the impact strength is required	Increasing parison temperature, slow down the mould cooling cycle, review the pinch-off angle of the mould. Add a reinforcing pinch off
Samples are shrinking too much. The container's critical dimensions are out	The closure skips the threads when dropped on the chime.	Reduce shrinkage by increasing cooling cycle time, decreasing the parison temperature, or by decreasing the mould temperature. Check the mould dimensions.
Moulding flaws. Evident by ripples in the material around the inside of the neck finish	Creates cracks in the material which act as sights on crack propagation. These reduce the fracture toughness of the container	Calibrate the blow pin. Check blow pin integrity. Straighten the blow pin. Clean the blow pin. Vent the blow pin. Ensure correct seating of the blow pin in the mould.
Contaminants. Evident by particles in the material	The act as stress concentrations and can reduce fracture toughness	Ensure clean material, remove impurities.

Common failure modes

Cracking of the body material about the inner shoulder of the neck finish. The crack is between the neck finish and the lifting handle.

Typically occurs when dropped on the chime (orientation 1). Failure occurs due to the hydraulic stress creating a stress concentration at a sharp corner. The stress exceeds the materials yield strength and cracks the material. Remedy recommendations include:

1. Add a large fillet to dissipate the stress concentration;
2. Check that there aren't any manufacturing flaws within the neck finish acting as sites for crack initiation; and/or
3. Possibly increase the material thickness in this area to increase the yield stress. Alternatively, you may decrease the material thickness in this area to improve fracture toughness.

Cracking of the body material about the inner shoulder of the neck finish. The crack is far-most away from the lifting handle.

Typically occurs when dropped flat on its side with the closure down (orientation 6). Failure occurs due to the hydraulic stress creating a stress concentration at a sharp corner. The stress exceeds the materials yield strength and cracks the material. Remedy recommendations include:

1. Add a large fillet to dissipate the stress concentration;
2. Check that there aren't any manufacturing flaws within the neck finish acting as sites for crack initiation; and/or
3. Possibly increase the material thickness in this area to increase the yield stress. Alternatively, you may decrease the material thickness in this area to improve fracture toughness.

Cracking of the body material along the top mould parting line

Typically occurs when dropped on the chime and flat on the side (orientation 1 and 6). Poor welds feel like a sunken void in the material and this acts as a stress raiser. Failure occurs due to the applied stress and the hydraulic stress creating a stress concentration along the notch line. The stress exceeds the materials yield strength and cracks the material. Remedy recommendations include:

1. Increasing parison temperature;
2. Slow down the mould cooling cycle;
3. Review the pinch-off angle of the mould; and/or
4. Add a reinforcing pinch off.

Cracking of the body material along the base mould parting line

Typically occurs when dropped flat on the side (orientation 6). Poor welds feel like a sunken void in the material and this acts as a stress raiser. Failure occurs due to the applied stress and the hydraulic stress creating a stress concentration along the notch line. The stress exceeds the materials yield strength and cracks the material. Remedy recommendations include:

1. Increasing parison temperature;
2. Slow down the mould cooling cycle;
3. Review the pinch-off angle of the mould; and/or
4. Add a reinforcing pinch off.

Dislodging of the closure

Typically occurs when dropped on the chime (orientation 1). The gasket has been compressed and the closure has deformed. These movements have caused the closure to skip the threads on the neck finish. Remedy recommendations include:

1. Ensure the closure is torqued up correctly. There will be torque loss after conditioning the jerrycans;
2. Check the critical neck dimensions. Ensure that the neck hasn't shrunk too much after moulding. The closure should tighten up smoothly without any distortion.
3. Check that the plastic isn't too ductile. The threads may be too weak to hold the closure.
4. Check that the threads are clean. The pinch lines may have excess material on them preventing good seating.
5. Increase the robustness of the closure;
6. Check the gasket integrity; and/or
7. Use a stiffer gasket to prevent excessive gasket compression.

Deformation of the neck finish

Typically occurs when dropped on the chime (orientation 1). Dropping on the chime causes the neck to oval and skip the wedge seal of the closure. Remedy recommendations include:

1. Ensure the closure is torqued up correctly (there will be torque loss after conditioning the jerrycans);
2. Reinforce the neck by increasing the material thickness;
3. Increase the robustness of the closure. Increase the wedge thickness; and/or
4. Ensure the wedge is seated tightly against the inside of the neck finish.

Support

That's it, you're at the end!

We're here to support you with any questions that you may have. Please feel free to get in contact with us and we'll share our insights.

Since it isn't vital to our customers, we didn't go into the variations of drop testing methods and their impact on test results. However, if you're interested on how we operate in the lab, then please get in contact.

Email: info@auscompliancelab.com.

Appendix A – Drop testing, UNRDG-20 clause 6.1.5.3

6.1.5.3.2 *Special preparation of test samples for the drop test*

The temperature of the test sample and its contents shall be reduced to -18 °C or lower for the following packagings:

(a) Plastics drums (see 6.1.4.8);

(b) Plastics jerricans (see 6.1.4.8);

(c) Plastics boxes other than expanded plastics boxes (see 6.1.4.13);

(d) Composite packagings (plastics material) (see 6.1.4.19); and

(e) Combination packagings with plastics inner packagings, other than plastics bags intended to contain solids or articles.

Where test samples are prepared in this way, the conditioning in 6.1.5.2.3 may be waived. Test liquids shall be kept in the liquid state by the addition of anti-freeze if necessary.

6.1.5.3.3 Removable head packagings for liquids shall not be dropped until at least 24 hours after filling and closing to allow for any possible gasket relaxation.

6.1.5.3.4 *Target*

The target shall be a non-resilient and horizontal surface and shall be:

(a) Integral and massive enough to be immovable;

(b) Flat with a surface kept free from local defects capable of influencing the test results;

(c) Rigid enough to be non-deformable under test conditions and not liable to become damaged by the tests; and

(d) Sufficiently large to ensure that the test package falls entirely upon the surface.

6.1.5.3.5 *Drop height*

For solids and liquids, if the test is performed with the solid or liquid to be carried or with another substance having essentially the same physical characteristics:

Packing group I	Packing group II	Packing group III
1.8 m	1.2 m	0.8 m

For liquids in single packagings and for inner packagings of combination packagings, if the test is performed with water:

NOTE: The term water includes water/antifreeze solutions with a minimum specific gravity of 0.95 for testing at - 18 °C.

(a) Where the substances to be transported have a relative density not exceeding 1.2:

Packing group I	Packing group II	Packing group III
1.8 m	1.2 m	0.8 m

(b) Where the substances to be transported have a relative density exceeding 1.2, the drop height shall be calculated on the basis of the relative density (d) of the substance to be carried, rounded up to the first decimal, as follows:

Packing group I	Packing group II	Packing group III
d ×1.5 (m)	d × 1.0 (m)	d × 0.67 (m)

6.1.5.3.6 *Criteria for passing the test*

6.1.5.3.6.1 Each packaging containing liquid shall be leakproof when equilibrium has been reached between the internal and external pressures, except for inner packagings of combination packagings when it is not necessary that the pressures be equalized.

6.1.5.3.6.2 Where a packaging for solids undergoes a drop test and its upper face strikes the target, the test sample passes the test if the entire contents are retained by an inner packaging or inner receptacle (e.g. a plastics bag), even if the closure while retaining its containment function, is no longer sift-proof.

6.1.5.3.6.3 The packaging or outer packaging of a composite or combination packaging shall not exhibit any damage liable to affect safety during transport. Inner receptacles, inner packagings, or articles shall remain completely within the outer packaging and there shall be no leakage of the filling substance from the inner receptacle(s) or inner packaging(s).

6.1.5.3.6.4 Neither the outermost ply of a bag nor an outer packaging may exhibit any damage liable to affect safety during transport.

6.1.5.3.6.5 A slight discharge from the closure(s) upon impact is not considered to be a failure of the packaging provided that no further leakage occurs.

6.1.5.3.6.6 No rupture is permitted in packagings for goods of Class 1 which would permit the spillage of loose explosive substances or articles from the outer packaging.

Appendix B – Water-hammer equations

These equations have been derived from B.E. Wylie and V.L. Streeter, *Fluid Transients in Systems*, Prentice Hall, 1993.

They assume that:

1. all deformation of the container is elastic;
2. neglects that the area increases due to tension; and
3. the fluid is pure without air being present.

For a rigid, elastic container:

$$c_{wave\ speed} = \sqrt{\frac{K_{bulk\ modulus}}{\rho_{density\ of\ liquid} \times \left(1 + \frac{K_{bulk\ modulus} \times \Delta A_{change\ in\ cross\ sectional\ area}}{A_{cross\ sectional\ area} \times \Delta P_{change\ in\ pressure}}\right)}}$$

Since the walls of a container are quite flexible, thus the denominator of KdetA/AdetP is very small and thus can be simplified to

$$c \approx \sqrt{\frac{A\Delta P}{\rho \Delta A}}$$

Thus, the wave speed can be expressed in terms of material properties and geometry.

For circular containers:

$$c_{circular\ container} \approx \sqrt{\frac{Et}{\rho D}}$$

Whereby D is the pipe diameter, t is the wall thickness, E is the modulus of elasticity, and ρ is the density.

For rectangular containers, the equation assumes that the container's cross section is perfectly rectangular, which is never the case due to edge fillets:

$$\frac{\Delta A}{A\Delta P} = \frac{B^4 \times RF}{15t^3 ED}$$

Whereby RF is the rectangular factor, B is the container's width, and D is its depth.

$$RF = \frac{6-5a}{2} + \frac{1}{2}\left(\frac{D}{B}\right)^5 \left[6 - 5a\left(\frac{D}{B}\right)^2\right]$$

$$a = \frac{1 + \left(\frac{D}{B}\right)^3}{1 + \frac{D}{B}}$$