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Charpy Impact Test of Cold Formed and Hot Rolled Steels Under Diverse Temperature Conditions

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Overview

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One of the more insidious types of failures that can occur in structures are brittle fractures, which are mostly due to either poor quality materials or poor material selection. Brittle fractures tend to occur suddenly and without much material inelasticity; think of a bone fracture, for example. These failures often occur in situations where there is little ability for the material to develop shear stresses due to three-dimensional loading conditions, where local strain concentrations are high, and where a logical and direct force path was not provided by the designer. Examples of this type of failure were observed in the aftermath of the 1994 Northridge earthquake in multi-story steel structures. In these buildings, a number of the key welds fractured without displaying any ductile behavior. Fractures tend to occur near connections, or at interfaces between pieces of base materials, as welding tends to introduce local discontinuities in both, materials and geometry, as well as three-dimensional stresses due to cooling.

When specifying materials for a structure that will see very low operating temperatures (i.e., the Alaska pipeline) many cycles of loading (a bridge on an interstate highway), or where welding is used extensively, it is necessary to have a simple test that characterizes the material's robustness, or resistance to fracture. In the civil engineering field that test is the Charpy V-notch test, which is described in this lab. The Charpy V-notch test is intended to provide a very simplistic measure of the material's ability to absorb energy when subjected to an impact load.

Principles

In metal structures, one is interested in obtaining ductile behavior, such that there is a sign or forewarning of impending failure. For example, in a steel beam, this might come in the form of excessive deformation. This performance is quantified through the material toughness, defined as the area under the stress-strain curve, which is the mechanical property most closely associated with ductile or brittle behavior. Toughness is related to both strength and ductility. While toughness is the ability of the material to plastically deform before failure, ductility is the measure of how much a material can plastically deform before failure. A material that has high strength but low ductility is not tough, just as a material with low strength and high ductility is not tough. In order for a material to be tough, it must be able to absorb high stress and high strain (ductility and strength).

The same material, a mild steel, for example, can behave in either a ductile or brittle fashion depending on the actual material chemistry, processing, and loading conditions. There are at least five main drivers for this possible change in performance:

1. The molecular and microstructure of the material, with finer grain sizes resulting in increases in strength and decreases in ductility, and the presence of large quantities of alloys, such as carbon, often resulting in a decrease of the ductility of most steels.
2. The processing that the material undergoes can result in different toughness in steel plates in the direction of rolling, perpendicular to it, and in the through thickness of the plate. This latter direction is particularly sensitive as it is hard to develop a consistent microstructure across a thick plate.
3. The loading conditions (loading in 3-dimensions), which often inhibits the development of the shear stresses. In 1- and 2-dimensional loading, one will generally encounter loading situations that give rise to large shear stresses, and thus a lot of yielding and ductile behavior. In the limit, for a 3D hydrostatic loading, there is no radius to Mohr's circle, and thus there is no shear. In such cases, the material will not yield but fail suddenly.
4. The increase in the strain rate, which leads to higher strengths but reduced deformation capacity.
5. A decrease in temperature, which can lead to significant decreases in toughness. Some materials that might be very ductile at room temperature might become very brittle if the temperature is significantly decreased.

To determine whether a material will behave in a brittle or ductile manner, one typically runs a Charpy V-notch impact test. There are other similar tests, such as Izod impact test, which is the most commonly used toughness test in Europe. These tests intend to measure the energy that a small volume of material can absorb when subjected to a sudden impact load. As noted earlier, this energy can be considered to be directly related to the area under the stress-strain curve.

Each Charpy V-notch specimen to be tested for resistance to impact has standardized dimensions and is designed, supported, and loaded so that it will fail when subjected to a single blow applied in a standardized manner. It is important to remember that the Charpy measurement is related to the volume and geometry of the specimen, and thus the results are useful for comparing the relative behavior of the materials and not for their absolute value.

To conduct the test, a small, beam-like specimen with a notch on one side (Fig. 1) is subjected to an impact from a hammer of a fixed weight dropped from a fixed height (Fig. 2). The weight is usually between 150 lbs and 300 lbs, and can be dropped for different heights to produce

different amounts of energy. The V-notch is designed to induce a stress concentration, thus significantly increasing the local stress. When the beam is simply supported on the two sides and struck down the middle, the beam will be bent in tension where the notch is. As a result, this will create a crack propagation through the specimen when struck.



Figure 1: Charpy specimen.



Figure 2: Charpy testing machine.

Theoretically, the potential energy stored at a given height of the hammer will be completely translated into kinetic energy just before the hammer strikes the Charpy specimen, assuming that the pendulum is frictionless. As the hammer strikes the specimen and it fractures, some amount of this kinetic energy is consumed. One then measures how much the pendulum swings back up in the opposite direction. From the difference between the initial height and the height achieved after the strike, one can compute a difference in potential energy. All the energy that has been lost in this process can be assumed to be absorbed by the test specimen in fracture. This value is considered to be equal to the toughness of the material, or the area under the stress-strain curve.

Many metals, especially the body-centered cubic (BCC) steels, exhibit a very sharp decrease in energy absorption at temperatures beginning around 40 or 50°F, and reach a lower plateau around -100°F. Numerous structures today exposed to the environment are within this temperature range, thus it is important to understand the temperature dependence of metal failure. For example, in constructing a pipeline in northern Alaska

where temperatures can reach very low values, it would be important to understand the temperature dependent failure of the metal. However, most face-centered cubic (FCC) steels, like stainless steels, are impervious to this temperature effect.

Theoretical fracture strength, also known as ideal fracture strength, is primarily dependent on the free surface energy and the interatomic distance. An ideal material will have a strength roughly 1/8 to 1/10 of its modulus of elasticity. The actual experimental fracture strength is much lower due to defects, voids, metal inclusions, and/or impurities. For example, in a simple steel bar loaded in tension, the stress is assumed to be uniform, except for near the ends where the load is being applied. However, with the introduction of a simple, circular hole, the forces have to flow around the hole, thus creating a stress concentration next to the hole.

The magnitude of the stress concentration is proportional to the radius of the hole to the width of the specimen (r/w). As the radius decreases, the stress concentration factor increases dramatically. However, there are no perfect holes in nature or man-made products; in general, there will be jagged edges at the microscopic level and thus stress concentrations much higher will occur. There are many imperfections and defects in metal crystal lattices. It is near these small stress concentrations that cracks begin to form, and when loaded very quickly, these cracks will propagate, coalesce, and ultimately cause the material to fail.

This test falls in the area of fracture mechanics, which involves characterizing a materials' ability to resist the formation and propagation of cracks. Linear elastic fracture mechanics (LEFM) is an energetics approach, wherein the total energy of the system is equal to the work due to applied loads plus the stored strain energy plus the energy required to create new fracture surface. In its linear fashion, it is very useful for characterizing brittle materials that exhibit limited plasticity. There are several limitations to LEFM as applied to the Charpy test, such as a false assumption that no energy is lost through plasticity, even though there is a lot of plasticity in front of the crack propagation.

Procedure

In this experiment we will test several Charpy specimens at different temperatures to illustrate the temperature effect on impact resistance of mild steel.

1. To prepare the testing machine, first make sure the path of the hammer is clear of any obstructions. Once the path is clear, lift the hammer until it latches and secure the lock to prevent accidental release of the hammer.
2. To prepare the specimens, use the cold box to cool one specimen of each metal to a temperature well below freezing. Use a hot plate to heat another specimen of each metal to a temperature above 200 ° F.
3. Once the hammer is raised, insert the specimen into the machine using tongs making sure it is centered in the fixture with the notch facing away from the side to be impacted by the hammer.
4. Once the specimen is ready, set the dial on the machine to exactly 300 ft-lbs. Important: Turn the dial using the knob. Do not push on the pointer!
5. To begin the test, remove the lock and release the pendulum by pressing on the lever.
6. After the specimen has been broken, the dial gage will read the energy absorbed by the specimen. Record this value.
7. Once the absorbed energy is recorded, you may use the machine brake to stop the pendulum from swinging. Since using the brake changes the gage reading, be sure to record the data before using it.
8. Once the pendulum has stopped, retrieve the specimen and determine the percent of area of the fractured face that has fibrous texture.

Results

After repeating the experiment for many specimens and temperature values, you can plot the temperature dependence of the energy absorbed and clearly see the existence of an upper and lower shelf (or flat horizontal portions). These shelves indicate that there are clear minima and maxima that can be achieved for a given material and processing. The main interest is in carefully quantifying the transition temperatures to minimize the risk that these fall within the operating temperatures of the structure being designed. Similar materials undergoing different heat and mechanical treatments will show somewhat similar upper and lower shelves, but also a distinct shift in the transition temperature. Moving the transition zone to the left will tend to lower the fracture risk for a structure; however, that entails significant additional costs in terms of processing.

It also should be noted that the Charpy test is useful for characterizing brittle materials, which will show very little ductility. In practice, Charpy tests are used for all types of materials, including very ductile metals. This use is fundamentally incorrect because the deformation processes driving a brittle failure are different from those in a ductile failure. It has not been possible to derive a simple test that can be used in a production setting, like the Charpy one, for semi-ductile or ductile materials. Thus, it is likely that the Charpy tests will remain popular in the near future.

Applications and Summary

Impact testing, in the form of Charpy and Izod tests, is commonly used to measure the resistance of metallic materials to brittle fracture. The Charpy test uses a small beam specimen with a notch. The beam is loaded by a large hammer attached to a frictionless pendulum. The combination of the strain rate from this loading sequence and the presence of the V-notch that creates a local large stress concentration result in fast crack propagation and splitting of the specimen.

The test determines the energy absorbed by the material during fracturing by comparing the potential energy at the beginning and ending of the test as measured from the position of the impact hammer. The magnitude of the energy absorbed is dependent on the volume of the material in the small beam specimen, so the results are valid only in a comparative sense.

Fracture mechanics is a very important field of studies in all materials, as it reminds us that all materials contain flaws that the shape and size of the flaw are important, and that one needs to address in design the issue of stress concentrations.

One demonstration of the importance of temperature dependence was in World War II when some Liberty ships and T-2 tankers literally split in half while still in port. For the Liberty ships, this failure had to do with stress concentrations that were induced during welding, as well as embrittlement of the steel hull due to welding operations and accompanied by cold sea temperatures.

The Charpy V-notch test is part of many ASTM standards, and as such, is present in many products that we use everyday. A particularly important application is in bridge design where most steels are specified to pass a low temperature and a high temperature Charpy limit (*i.e.*, 20 ft-lbs at -40°F and 40 ft-lbs at 80°F).

Fracture energy is a very important material property. If one tests a flawless glass plate with surface energy $\gamma_s = 17 \times 10^{-5}$ in-lb/in² and $E = 10 \times 10^6$ psi, the theoretical fracture strength would be about 465,000psi, given Griffith's equation ($\sigma_f = (2E\gamma_s/\pi a)^{0.5}$). If one introduces a flaw, even with a magnitude as small as 0.01in, into the glass plate, the fracture strength is reduced by three orders of magnitude to only 465psi, which is much more like what we see in real life.

Other temperature dependent applications for which a Charpy v-notch test would be important include testing equipment for space travel, where the temperature varies over a great range, as well as for sledding equipment in Antarctica and other polar regions, where temperatures dip well below zero.