Brittle fracture of Liberty Ships

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(Summary)

As part of the government project during World War II, United States planed continuous block construction of all-welded cargo vessels (DWT 11000, "Liberty Ship"). The construction was started with outbreak of the Pacific war from 1942.

2708 Liberty Ships were constructed from 1939 to 1945. 1031 damages or accidents due to brittle fracture were reported by April 1, 1946. More than 200 Liberty Ships were sink or damaged beyond all hope of repair. "Schenectady" is one of those, which broke in two with a large sound when it was moored at wharf (see Fig. 1).

The accident was caused by occurrence and development of brittle crack, which were due to the lack of fracture toughness of welded joint. The accident should be the most expensive and huge scale experiments of the century. The accident showed importance of fracture toughness, which marked the birth of the fracture mechanics.

1. Component

Cargo vessel “Schenectady” (DWT 11000 Liberty Ship) (T-2 tanker)

2. Event

By executive order of President Roosevelt, the United States started the production of all-welded cargo vessel (DWT 11000 Liberty Ships) in 1942 in order to meet the demands of the Pacific War.

These cargo vessels were used as troopships of large amount of military logistics to ensure eventual US victory in the Pacific. These ships were, therefore named “Liberty Ships.”

Nineteen pre-existing shipyards and eighteen newly built shipyards were set aside for the exclusive construction of the Liberty Ships. A total of thirty-seven factories worked night and day on an assembly line in order to produce the Liberty Ships. Welded structure of the ship enable the continuous block manufacturing. This manufacturing method of cargo ship was similar to that used in Japan during the same period.

Since the outbreak of World War II in 1939, the US had been constructing warships. However, the scale involved in the Liberty Ship construction for the Pacific War was amazing. Between 1939 and 1945, the thirty-seven shipyards produced 5,777 ships (2,708 were Liberty Ships) which were equivalent to DWT 56 million.

Many damages and accidents of cargo vessel were occurred, and especially for Liberty Ships. The vast majority of these accidents were related to brittle fracture. By 1st of April 1946, 1441 cases of damage had been reported for 970 cargo vessels, 1031 of which were to Liberty Ships. Total numbers of 4720 damages were reported.

These numbers vary by source. Parker's work states that the number of construction of cargo vessel was 4694 and that the number of damaged Liberty Ships was 1289 with 233 being sunk or incurring serious damage. It is important to keep in mind the discrepancies due to the difference of assortment and counting period.

Occurrence and progress of brittle cracks may result in catastrophic failure if the condition is satisfied. In January 1943 at the Oregon shipyard, the Liberty Ship "Schenectady" suddenly broke in two with a large sound when it was mooring at outfitting basin. In March 1943 at the outside New York port, “Manhattan”, which was on sailing, was also broke in two. A total of seven ships were broken like this.

3. Course

A committee for investigating these accidents of cargo vessels was established in 1943. The report completed three years thereafter on July 15th, 1946, and the committee was dissolved.

The investigation into the cause of the accidents was wide-ranging and systematic research on structure and welding. The interim report suggested the importance of modification of structural design that reduces stress concentrations, improvement of weld quality that eliminates initial defect, and reduction of residual stresses by welding. However, the lack of steel toughness was not sufficiently recognized; insufficient attention was paid for the material. It was only considered that “rimmed steel” is preferred than “killed steel”. So-called “welding steel” which possesses superior fracture toughness and weld crack resistance was not used in the wartime. The production of the welding steel was started after the war. It was regulated to use for vessel's body later.

The final report concluded that the number of accidents due to welding structure was statistically small and it will have no problem by the countermeasures. It is also stated that the construction of the large number of cargo vessels enable the transportation of military logistics which helped the victory. Overall the project, therefore, was thought success. The results of this report show US nationality of positive philosophy which kept affirming the welding joints in spite of the many accidents. The Liberty ship program had technical problems, but when combined with victory in World War II, it was hailed as a success. This program which depends on the strength of US's material superiority was just like US. Technology progresses with failures.

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4. Cause

At the present day, it is thought that the low weldability of steel was the main cause of the accidents. Furthermore, secondary causes included both the stress concentration due to poor design and initial defect of welding.

Steel experiences ductile fracture at high temperatures and brittle fracture at low temperatures; therefore, steel shows the characteristic of ductile-to-brittle transition. Brittle fracture usually occurs under the conditions of low-temperature, high-loading rate, and multi-axial stress constraint, which can be evaluated by Charpy Impact Test. Absorption energy measured by the test is called the notch toughness. Low notch toughness at low temperature is often the cause of brittle fracture. In other words, notch toughness at low temperature should be high to prevent brittle fracture. The low weldability of steel induces both a reduction of notches toughness at low temperature and weld crack.

The brittle fractures that occurred in the Liberty Ships were caused by low notch toughness at low temperature of steel at welded joint, which started at weld cracks or stress concentration points of the structure. External forces or residual stress due to welding progress the fracture. Almost all accidents by brittle fractures occurred in winter (low temperature). In some cases, residual stress is main cause of fracture, which was typified by the accident of Schenectady ship.

5. Immediate Action

The Liberty Ship accidents generated international interest in developing high weldability steels. The conclusion is to increase notch toughness at low temperature. Metallurgical improvement such as low carbonization or addition of deoxidization element Mn and Si is effective to prevent weld crack.

On the other hand, theory of fracture mechanics that was originated in physics was applied to the problem of brittle fracture. And then, fracture mechanics were systematized in the engineering mechanics field. This takes the form of expressing the intensity of a stress field around a crack tip through the use of the stress intensity factor K. If this value exceeds the fracture property Kc of the material then fracture may occur. Fracture property of material Kc is called fracture toughness. Fracture toughness was taken over the notch toughness. The introduction of fracture mechanics has made the quantitative assessment of fracture toughness possible. As a consequence, brittle fracture accidents rarely occur now.

6. Countermeasure

- Use of high weldability steels in order to ensure notch toughness at low temperature.
- Quantitative assessment of brittle fracture by fracture mechanics.

7. Knowledge

Through the Liberty Ship accidents, several problems of welding structure - such as fracture toughness at low temperature, weld defect, residual stress due to welding, and welded structures which could not prevent crack growth as compared to the riveted structures - became clear. The realization of these problems marks the start of the discipline of fracture mechanics.

The important precept was, however, the size effect which affect the fracture pattern. The main material of ship is low carbon steel. Small size specimen test of the steel shows elongation before fracture (plastic collapse) while large structure made by same material shows almost no plastic deformation (fracture toughness). Even ductile materials, therefore, shows same fracture pattern as brittle materials.

8. Background

Iron manufacturing technology has completed in 19th century. The 20th century was the century of mass production and consumption of iron and steel. At the beginning of the 20th century, the center of iron and steel manufacturing moved from Europe to the US. The firm, "US Steel," had a steel output that matched the entire German steel production. Furthermore, the two world wars caused large increases in steel consumption. As a consequence of the resultant increase in steel production, accidents related to fracture of iron and steel started to increase. In order to cope with increased demand, the welded joint was used to replace the riveted joint. The large number of accident related to brittle fracture that occurred at welded joint led to the systematization of fracture mechanics.

9. On the Side

Griffith is generally considered to have founded fracture mechanics in 1921, but in truth it was probably Charpy in 1912. As fracture has been a problem for human being from the use of tools, a few papers about fracture were reported even before 20th century. From the 19th to 20th century after the industrial revolution (from the 18th to 19th centuries), heavy industry was blooming business. As a result, however, many accidents related to brittle fracture were experienced. These accidents were due to the lack of understanding of the ductile-to-brittle transition characteristics of steels, which were never recognized before. Engineers were confused because high strength and ductile steels showed low strength and brittle property which were never expected. Charpy clarified the ductile-to-brittle transition property of steels and developed the Charpy Impact Test to evaluate it.

In general, small test pieces subjected to tensile loading at room temperature fracture in a ductile manner after plastic deformation whereas large sections, especially at low temperatures, fail at less than their maximum tensile strength, a phenomenon that is known as brittle fracture.

Brittle fracture is usually caused under the conditions.

(1) Low temperature

(2) High deformation rate

(3) Increase of plastic constraint (or triaxial stress) due to large size or existence of structural discontinuities such as notches

It is required to have sufficient toughness or low ductile-to-brittle transition temperature under service conditions.

The Charpy Impact Test can evaluate the ductile-to-brittle transition. The test uses a specimen with a notch which gives strong plastic constraint. Absorption energy is measured with various specimen temperature (this is not ambient temperature) by applying a hummer impact to obtain high deformation rate (see figure 2).

The objectives of the Charpy Impact Test is to determine:

(1) Absorption energy

(2) Ductile-to-brittle transition temperature (see figure 3)

Although absorption energy is a qualitative value to evaluate materials, the amount can not be used directly to the design in the same way as fracture toughness which is expressed by stress intensity factor.

It is very useful to know ductile-to-brittle transition temperature of steels. A component can operate without the risk of brittle fracture if the service temperature is above the ductile-to-brittle transition temperature. As the plastic constraint and the deformation rate in the test is generally more severe than actual plastic constraint and in-service deformation rates, the ductile-to-brittle transition temperature predicted by the test will results in a conservative estimate. Material and design standards often specify the absorption energy rather than a particular ductile-to-brittle transition temperature. This regulates the absorption energy of upper shelf at specified temperature. Specified temperature is above the ductile-to-brittle transition temperature. Specifying the absorption energy is, therefore, essentially the same as defining a ductile-to-brittle transition temperature.

The Charpy Impact Test is simple and convenient, which is why it has been used for a century. Even in the field of nuclear power plant, which is most advanced application field of fracture mechanics at present, reduction of fracture toughness due to neutron radiation is predicted by Charpy Impact Test. In summary, fracture mechanics in the 20th century began and ended with the Charpy Impact Test.

10. Primary Scenario

01. Unknown Cause
02. Occurrence of Unknown Phenomenon
03. Insufficient Analysis or Research
04. Insufficient Prior Research
05. Lack of Reexamination/Review
06. Production
07. Hardware Production
08. Ship Building
09. All-welded Construction
10. Rejection of the Use of Weldability Steel
11. Lack of Notch Toughness at Low Temperature
12. Failure
13. Fracture/Damage
14. Brittle Fracture
15. Failure
16. Large-Scale Damage
17. Hull Breakage
18. Loss to Organization
19. Economic Loss
20. Delay of Termination of the War

Fig. 1 Cargo vessel “Schenectady” which suffered catastrophic failure in calm harbor.

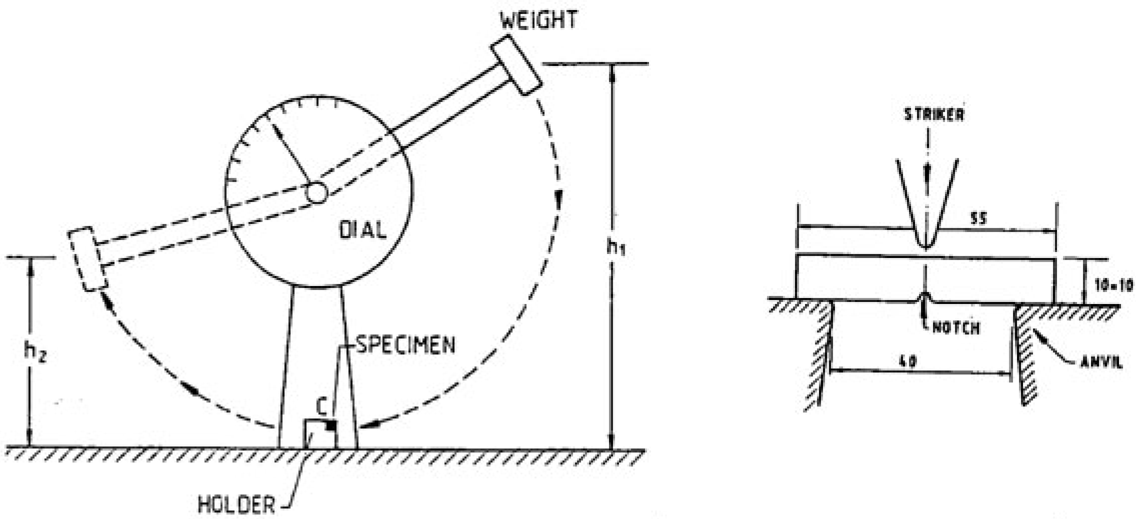

Fig. 2 Charpy Impact Test.

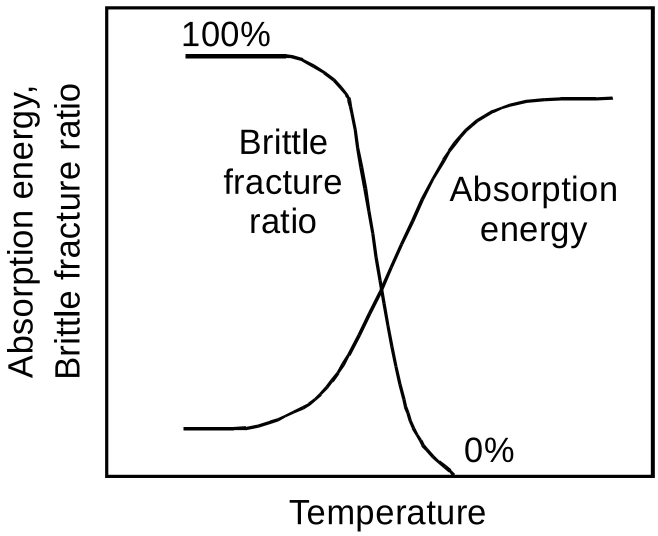

Fig. 3 Absorption energy, brittle fracture surface ratio vs. temperature.