Large scale physical model testing on the ultimate compressive strength of a steel stiffened plate structure at cryogenic condition

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Abstract

Ship structures are typical examples of large plated structures which are made of large number of structural elements composed into system structures to be strong enough, while keeping the structural weight at minimum, to survive varying loads arising from cargo (e.g. weight and cryogenic condition due to LNG cargo), waves, winds or other environmental conditions (e.g. cold temperature due to Arctic operation). The design of ship structures are today designed based on limit states which are defined by the description of a condition for which a particular structural member or an entire structure would fail to perform the function designated beforehand. Four types of limit states are relevant, namely SLS (serviceability limit state), ULS (ultimate limit state), FLS (fatigue limit state) and ALS (accidental limit state). At the preliminary design stage, structural scantlings and materials of ship structures are determined based on the ULS, and ultimately other types of limit states are integrated to ensure so that the different parts of a ship structure will meet safety requirements and survive environmental and operational conditions during the life time period of some 25 years.

The stiffened plate structures in the bottom, the deck and the side-shell are the most important parts of a ship in association with a ship's integrity, safety and survivability. The design criteria for determining the scantlings of stiffened plate structures are the ultimate limit states (or ultimate strength). If applied loads exceed the ultimate strength then the stiffened plate structures fail to perform the function, leading to total loss of the ship. Therefore, it is of vital importance to accurately and efficiently compute the ultimate strength of stiffened plate structures.

The behavior of stiffened plate structures until and after the ultimate strength is reached is highly nonlinear involving geometric nonlinearities (e.g. buckling and large deflection) and material nonlinearities (e.g. yielding, plasticity and material failure or fracture). Various types of collapse modes, including overall buckling collapse, beam-column type collapse, web buckling induced collapse and flexural-torsional buckling induced collapse, are relevant. Today's large merchant ship structures are made of different grades of steel materials that should meet specific requirements for yield strength, ductility, brittleness, ultimate tensile strength resistance to corrosion in association with operational and environmental conditions.

As of today, the ultimate strength of stiffened plate structures has been studied and applied in room temperature conditions.

However, ships now operate in Arctic region at cold temperatures as climate change causes Arctic ice to melt at an alarming rate. A shipping company MAERSK recently navigates a 200m long container ship through the Arctic waters for the first time without the help of icebreakers. The average ambient temperature in Arctic region during winter season is -40 deg. C and the lowest temperature is reportedly -68 deg. C. Furthermore, the number of LNG-fueled ships is increasing in terms of resolving the issues associated with CO2 emissions. LNG-fueled ships need to have LNG fuel tanks in a large size, and hazards of LNG leakage always exist. The temperature of LNG is -163 deg. C. The collapse behavior of ship stiffened plate structures is vulnerable to cold temperatures or cryogenic condition in association with catastrophic failure, leading to total loss of ships that can affect personnel, assets and the environment, where brittle facture must be playing a significant role on the ultimate strength behavior.

Theoretical methods are almost impossible to apply for computing such a highly nonlinear behavior of ship stiffened plate structures involving buckling, yielding and brittle fracture. Advanced computational models should be developed for that purpose. However, it is highly demanding to obtain physical model test database which shall be used to validate the accuracy and applicability of the advanced computational models.

The purpose of the present study is to obtain physical model test database on the ultimate strength characteristics of ship stiffened plate structures subject to extreme loads and cold temperatures (due to LNG leakage). Physical model testing on a large scale ship stiffened plate structure is undertaken at cryogenic condition (-160 deg. C). Elastic-plastic large deflection behavior of the test model under axial compressive loads is measured until and after the ultimate strength is reached. Material properties at cryogenic temperature are tested in separate material experiments. Details of the test database are documented.

Keywords: LNG; Cryogenic condition; Brittle fracture; Steel stiffened plate structure; Ultimate compressive strength; Physical model testing, Test database