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Influence of Raised Invar Edges on Sloshing Impact Pressures

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This paper presents an investigation of the influence of raised invar edges on tank sloshing under partial-fill conditions. Through multiple-scale wedge drop tests and 2-D sloshing model tests, the authors were able to show that raised invar edges tend to enhance the magnitude of sloshing pressures. The enhancement effects were found to be highly localized and to vary with the size of the loaded area. The findings from this work emphasize the importance of considering the physics of invar edge effects in defining the design pressure to be used in assessing the integrity of membrane LNG tanks.

INTRODUCTION

Safe design of Membrane Insulation Systems (MIS) in LNG ships requires the adequate assessment of sloshing loads and structural capacities. Dynamics of the MIS structural designs require that sloshing pressures be defined with fine spatial and temporal resolution on the order of 0.1 square m and 10^{-4} s, respectively. The requirement of fine spatial and temporal resolution has posed significant challenges to analytically based methodologies for the prediction of sloshing impact pressures. In the past, researchers have conducted model-scale sloshing tests in order to define prototype design pressures for structural integrity assessment (Bass et al., 1980), although using tanks with smooth walls. However, at prototype scale, the 2 widely used MIS systems both have raised elements, corrugations in the case of MKIII and raised invar edges in the case of No.96. The MKIII primary membrane includes a square pattern of corrugation cells formed by the crossing rows of larger and smaller corrugations, both with spacings of roughly 340 mm. In the case of the No.96 system, parallel rows of raised invar edges are present with spacings of roughly 500 mm and contain the weld used to join the invar sheets that make up the primary membrane. Recently ExxonMobil has developed sloshing assessment methodologies (Sandström et al., 2007; Kuo et al., 2009) using corrugated tanks for assessing the integrity of the membrane LNG containment systems.

Some studies have been performed to understand the influence of corrugations on sloshing pressure. Due to the complexity of sloshing model tests, researchers have often used the well-defined wedge entry problem as a means of understanding the basic effect of corrugation. Wedge drop tests have been widely used in the industry as a means to investigate fluid impact problems, partly due to the existence of analytical and numerical solutions for the wedge entry problem. Wagner (1932) first developed a 2-D theory to study the vertical entry of a wedge and to calculate the local impact pressures, but his solution is only applicable when the dead-rise angle of the wedge (the angle between the wedge surface and the water surface) is not small, and when air trapped between the wedge and the water surface is negligible.

Chuang (1967) carried out a series of experiments to study the effects of the dead-rise angle on a rigid wedge slamming in water. Based on measurement and a high-speed underwater video, he reported that air was trapped between the impact wedge surface and the water surface for very small dead-rise angles (less than 3°). Such trapped air provided cushioning during the impact, resulting in lower measured impact pressures. For a wedge with a dead-rise angle of 3° and more, most of the air had escaped at the instant of impact.

Zhao and Faltinsen (1993) developed a numerical method to study the water entry of a 2-D body. Their method was based on assumptions of zero gravity, incompressibility and nonviscous fluid without air cushioning effects. For small dead-rise angles above 3°, they developed a simple formula to estimate impact pressure based on Wagner's local jet flow analysis in combination with matched asymptotic expansions.

One study (Claude and Rico, 1993) suggested that the cushioning effect of trapped gas pockets is one main advantage of the corrugations for the integrity design of membrane LNG tanks. In another study (Ha et al., 2005), the authors summarized results from drop tests using wedges with dead-rise angles between 1.5° and 6° and drop heights from 1 m to 6 m. The reported pressure reduction factors ranged from 2.5 to around 12.5. In addition, the authors also carried out wedge drop tests into water of full-size corrugation panels (with 9 corrugation cells) with 0.5 m to 3.0 m of drop height and 0° to 45° of dead-rise angles. In these tests, 9 pressure sensors were distributed nonuniformly, and the pressures reported were the average of the maximum pressure of all sensors. The studies showed a minimum reduction factor of 2.0.

One primary conclusion from the earlier drop test studies was that corrugations significantly reduce the magnitude of impact pressures by factors of 2 to 3 when compared to pressures measured on the smooth side of the wedge. This result was due to the trapped air cushioning effect. Based on this finding, reduction factors of 2 to 3 have been proposed for use in estimating sloshing pressures for the structural integrity assessment of corrugated membrane LNG tanks.

A recent study (Yung, Ding and Kuo, 2008) showed that the corrugation effects on sloshing pressures are complex and may not be generalized as cushioning based on wedge drop testing alone. These conclusions were based on 2-D sloshing tests under both high-fill and partial-fill conditions. The tests showed that the impact pressures can either increase or decrease when compared to those on smooth walls under high-fill conditions due to local effective density change under the influence of bubble entrainment. For sloshing in a partially filled tank, consistent pressure enhancement was observed.

The purpose of this paper is to present findings of a study of the influence of raised invar edges on sloshing pressure. This work

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KEY WORDS: LNG carrier, membrane containment system, raised invar edges, liquid sloshing.