Sloshing Impact of LNG Cargoes in Membrane Containment Systems in the Partially Filled Condition

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ABSTRACT

LNG carriers have usually operated in the fully loaded condition or with a minimum filling of liquid cargo for the tank cooling-down purpose during the ballast voyage. The typical filling level of the LNG tank is greater than 95 percent of the tank height in the fully loaded condition and less than 10 percent in the ballast condition. Recently however, there has been growing demand for membrane-type LNGCs that can operate with cargo loaded to any filling level. This demand stemmed from the emergence of a spot market for LNGCs. LNG FPSO/FSRUs and their shuttle vessels must also be able to operate in the partially loaded condition. The sloshing load at filling levels other than the fully loaded or ballast condition is the main concern for vessels operated in this manner. In particular, the sloshing impact load on the insulation system and hull and the dynamic load on the pump tower at the low-filling levels is of particular concern in light of the previous history of damages. As a consequence, ABS has undertaken a comprehensive analysis of the new patterns of sloshing loads in the partially filled condition. This has included:

- Evaluation of the extreme ship motion in the North Atlantic Ocean with service life of 20–25 years
- Determination of ship motion condition that gives most critical sloshing load
- Time domain simulation of the sloshing motion
- Calibration of the sloshing load for scale effect
- Evaluation of the factor of safety of the insulation system
- Evaluation of dynamic load factor for hull scantling
- Structural analysis of pump tower

This paper describes the method of approach to these sloshing issues, with the emphasis on the difference in the sloshing load at the high- and low-filling conditions.

KEY WORDS: Sloshing; partial filling; LNG carrier; pump tower; insulation box.

INTRODUCTION

LNG carriers have usually operated in the fully loaded condition or with a minimum residue of cargo during the ballast voyage. The typical filling level of the LNG tank is greater than 95 percent of the tank height in the fully-loaded condition and less than 10 percent in the ballast condition.

Early designs of membrane LNG tanks experienced a number of incidents involving minor damage at the insulation box when in the high filling condition. Damages in the low filling condition were also reported. These have been very limited, occurring primarily when the No.1 cargo tank was loaded to between 15 and 20 percent of the tank height to provide LNG as coolant for other empty tanks during the ballast voyage.

Class societies, containment system designers and ship operators have conducted thorough studies of these damages. In every instance the sloshing of the cargo was identified as the cause of the damage. Simple but effective plans were proposed to counter the sloshing impact. The height of the chamfer at the topside was increased and the insulation box at the tanktop was reinforced to withstand the sloshing impact in the fully-loaded condition.

To prevent the adverse impact of sloshing in the ballast condition when LNG is carried for system cooling, the filling level is restricted to under 10 percent of the tank height. If this limitation is adhered to, no design change of the lower part of the tank has been required. No subsequent significant damage to the insulation system due to sloshing has been reported. The current design practice (tank scantling and insulation system) is effective in preventing the sloshing impact load under these restricted operational conditions.

Recent newbuilding demand has been for membrane-type LNG carriers. Coincidentally, market forces have indicated a need for LNG carrier designs able to operate in the partially-loaded condition on an emerging spot market. These two factors have necessitated specific analysis and criteria for partial loading of membrane tanks.

Additionally, LNG FPSO/FSRUs and their shuttle vessels must also be able to operate in the partially loaded condition. The sloshing load at filling levels other than the fully loaded or ballast condition is the main concern for vessels operating in this manner. In particular, the sloshing impact load at the low-filling levels is of particular concern in light of the previous history of damages.

As a consequence, ABS has undertaken a comprehensive analysis of the new patterns of sloshing loads in the partially filled condition to determine the factor of safety of the insulation system, identify required scantlings of the tank structure and analyze the need for reinforcement of the pump tower and the connecting structure to the hull.

The following discussion addresses the central elements of the analysis and explains the difference in the liquid motion at the high- and low-filling levels.
Liquid Motion at High- and Low-Filling Levels

Experiment and numerical simulation both show that the sloshing motion in an LNG tank at the low-filling level is quite different from that experienced at the high-filling level. In the latter case, standing wave motion is observed in the tank. Since the amplitude of the wave is restricted by the gap between the liquid level and the tank top, there is no significant liquid motion inside the liquid domain. Pressure distribution is almost hydrostatic except near the tank top.

However, near the top of the tank, the interaction between the standing wave and the tank top generates a rapid change in the fluid velocity, which results in large accelerations of the fluid particle and pressure gradient. A typical pressure distribution at the high-filling level can be seen in Figure 1(a).

At the low-filling level, where the filling height is less than 20 percent of tank width (for lateral motion) or length (for longitudinal motion), hydraulic jump or bore can be found in the tank, as can be seen in Figure 1(b). The liquid motion is almost uniform over the depth.

When the tank motion is large, the front of the hydraulic jump becomes steeper, developing a breaking wave. If the hydraulic jump hits the bulkhead before breaking, large impact pressure can occur. The uniform velocity of the hydraulic jump also results in a large drag force on the lower part of the pump tower and its supporting system.

Sloshing impact occurs when there is a sudden change in the wetted area due to the liquid motion in the tank. In the fully-loaded condition, the tanktop is the only location exposed to the impact load. In the partially filled condition, a wider area on the tank wall is vulnerable to the impact load. The lower knuckle points at the upper chamfer may suffer large impacts when the crest of the standing wave at the tank wall reaches them. The impact at the knuckle point is similar to the slamming impact on a wedge.

The transverse and inner-skin bulkhead will also be exposed to impact from the hydraulic jump that is breaking or reflected at the tank walls. Since the insulation system at the lower part of the tank has less strength than the upper part, more careful assessment of the impact load at the low-filling level is required. Strengthening of the tank structure at the lower part may be required. Also affected is the pump tower design due to the increase in the drag force induced by the flow velocity in the hydraulic jumps.

Sloshing Analysis Method

Sloshing load is evaluated by a time-domain simulation of sloshing with the tank motion determined from the ABS Dynamic Load Approach (SH-DLA). The design load on the structures is obtained using the most critical sea condition to maximize dominant load parameters (DLP). The following three approaches have been used to determine the most critical condition.

- Dominant load parameters of roll, pitch and tank acceleration
- Excitation at tank resonance period
- Consideration of all wave frequencies and headings within the critical sloshing range

The first approach is the same as the conventional SH-DLA for the hull structural analysis. The second approach is introduced to consider the resonant liquid response due to sloshing. The third is a more direct but systematic and complete approach to be used at the final design stage or in those cases when a strictly conservative analysis is required. The first two approaches are used at the early design stage. All three approaches are described in more detail below:

First, the extreme values of the ship motion predicted during its 20 - 25 years of service life, using North Atlantic unrestricted service criteria, are evaluated using a ship motion program.

Once the extreme ship motion is identified, the appropriate ship motion to be used in the time domain sloshing simulation or model test is determined. The DLPs to be used in the sloshing analysis are in two categories. The first is to maximize the ship motion regardless of the filling level or resonance of the tank (ship-motion DLP). The second category is to maximize the resonance of the liquid motion in the tank for each filling level (tank-resonance DLP).

Currently ABS uses the following DLPs: roll, pitch, vertical, longitudinal and transverse acceleration at the center of the tank. As the tank-resonance DLP, ABS uses transverse acceleration at the roll resonance and vertical and longitudinal acceleration at the pitch resonance.

The excitation period of the tank is taken from the encountering period of the ship motion when the Response Amplitude Operator (RAO) of the DLP is at the maximum. The effective wave amplitude is limited by the breaking limit of the incoming wave for the given wave period to prevent the unrealistic wave amplitude when the RAO of the DLP is too small.

Figure 2 shows the roll and transverse acceleration RAO, which governs the transverse sloshing motion. The colored contour indicates the level of RAOs and the line contour is the encountering period to be used for tank motion. The dashed contour levels indicate the range of the sloshing resonance condition for filling levels from 70 percent to 90 percent of tank height. It can be seen that the maximum roll condition is removed from the resonant range, whereas the maximum condition for the transverse acceleration is close to the resonance at 70 percent filling level.
If the condition for the maximum ship motion and the sloshing resonance is not close, the wave conditions determined from the SH-DLA approach may not provide the most critical condition for sloshing load. When a more thorough search for the most critical condition is necessary, it is recommended that all possible wave frequencies and headings should be examined to find the most critical sloshing load (Advanced DLA).

At each wave frequency and heading, the effective wave amplitude is determined such that ship motion and other DLPs do not exceed the extreme values. The wave height is also limited by the breaking limit.

Figure 3 shows the color contour levels of the sloshing pressure at the filling levels of 70 percent, 80 percent and 90 percent. The dashed contour level represents the resonance condition for each filling level. Obviously, the maximum sloshing condition is away from the maximum-roll condition. The maximum transverse acceleration condition slightly misses the maximum sloshing condition.

Advanced DLA usually provides a sloshing load up to 20 percent higher in value than the original SH-DLA. This difference could be minimized through the application of a more appropriate DLP for sloshing load, such as the combination of the motion acceleration, velocity and the tank resonance. A development for the new DLP by parametric study of the detailed SH-DLA is in progress.

Once the most critical condition for the sloshing is identified, direct simulation of the sloshing in time domain is made to calculate the impact pressure and flow velocity in the tank. A finite-element code for sloshing analysis, SLOFE [1] is used to simulate the sloshing motion in the LNG tank.

Time history of the impact pressure on the bulkhead, and the flow velocity and acceleration at the pump-tower location, is recorded to evaluate the maximum load on the insulation system, tank structure and pump tower. The impact pressure, however, cannot be directly used for the structural analysis of the insulation system or tank structure. The impact pressure should be calibrated to consider the cushioning effect due to liquid-gas interaction in the full-scale LNG tank.

The impact pressure is further reduced as it transmits through the insulation system. Dynamic analysis is performed to evaluate how much impact load can be transmitted to the tank structure. The transmitted load is also used to evaluate the static equivalent load for hull scantling purposes.

The next step in the ABS approach is to calculate and calibrate the sloshing impact pressure for the assessment of the safety of the insulation system. Also addressed is the evaluation of the dynamic load factor to determine the static equivalent load for hull scantling and for structural analysis of the pump tower.

Impact Strength of the Insulation System

Plywood boxes (No. 96 system) or polymer foams (Mark III system) provide the main strength of the insulation system. Experiments have been performed to determine the impact strength of the plywood boxes and the foam. Dropping mass or explosives on the insulation system simulates the sloshing impact in the experiment. Both the magnitude and the duration of the impact load are important elements in the evaluation of the impact strength [2].

ABS is closely reviewing the experimental reports from the manufacturer to determine if the impact load identified at the test has similar magnitude and impact duration to the real sloshing load in LNG tanks. In many experiments the tested impact load could not reach the failure threshold of the insulation box. Only the maximum load tested in the experiment was used as the impact strength of the insulation system. This resulted in a somewhat conservative value for the impact strength.

There are also other sources of conservatism in the experiments. For example, the liquid-structure interaction is not considered in most instances. The interaction with liquid generally introduces added mass and results in a longer natural period of the insulation system. This should reduce the dynamic load factor and the actual load on the structure. More careful and advanced experiments are necessary for more accurate determination of the impact strength.

Sloshing Impact of LNG Cargoes in Membrane Containment Systems in the Partially Filled Condition
Once the impact strength of the insulation system is identified, it is compared with the actual sloshing load estimated by experiment or analysis, to evaluate the factor of safety of the insulation system. This is defined as the ratio of the impact strength divided by the impact load. It is a common practice to take the factor of safety 2 as the acceptance criteria for the insulation system.

**Sloshing Impact Load at Low Filling Levels**

The estimation of the sloshing load has usually been made from model tests. The motion of the tank is obtained either from the numerical calculation of the ship motion or from the observation of real ship motion. Inside the model tank, water is usually used as the liquid cargo and the void space is filled with air. This water-air condition is different from the real condition in the full-scale LNG carrier. The real LNG tank is filled with liquid methane and methane gas, which have different mechanical and thermodynamic properties. Since the LNG tank is always under the cryogenic condition, the void space of the LNG tank is filled with dense LNG vapor. At the atmospheric pressure, the density of the methane gas is about 0.4 percent of the LNG, whereas the density ratio between air and water is only 0.1 percent. As a result, more interference between the gas and liquid is expected in the real LNG tank. This interference is more important at the high-filling condition, where the sloshing impact mainly happens at the tank top when the crest of the liquid surface hits the top of the tank in normal direction. Because of the liquid-gas interference, a gas pocket is developed between the membrane surface and the upper surface of the sloshing wave. The entrapped gas in the pocket has a cushioning effect that significantly reduces the impact pressure. This pressure reduction, due to cushioning, has been observed in the slamming test at the low incident angle, as shown in Figure 5.

It should be noted that the amount of the entrapped gas depends upon the density ratio between liquid and gas. Slamming tests with lighter gas showed less gas entrapment and less cushioning [6], which implies that a greater reduction of impact pressure due to cushioning is expected when heavier gas is used.

The measured impact pressure at the water-air model test cannot be simply extrapolated to the full-scale pressure on the LNG tank because of the difference in the liquid-gas density ratio. To overcome this difficulty, pending further analysis, an ad-hoc approach has been adopted to estimate the impact pressure in the full-scale tank.

The impact pressure measured at the model tank is directly equated to the known impact pressure in the real LNG tank. The impact pressure in the full-scale LNG tank has not yet been measured. Instead, the strength of the insulation box in the previous damage case has been used as a reference impact pressure. For example, model tests of an LNG tank in a 130,000 m³ class LNG carrier have been performed to simulate the sloshing damage in the fully-loaded condition.

The insulation boxes at the top corners of the tank in the real ship have been slightly damaged in a severe pitching motion. The impact strength of the insulation box has been known as 6 bar. Impact pressure of 0.890 bar has been measured in the 1/70 scale model filled with water and air. The ratio of these two pressures at the full- and model scale tank has been used as the scale ratio of the impact pressure for other LNG tanks.

By directly evaluating the impact pressure in full scale from the model test result by similarity law, without any consideration of the cushioning effect, and then comparing it with the impact strength of the damaged insulation box, an estimated reduction in the pressure level can be determined. Although this calibration is derived from the fully-loaded condition, specifically at the 96 percent filling level, the same calibration factor has been used to evaluate the impact pressure at other filling levels.

Similar pressure reduction has been observed in the model test with LPG [4]. Figure 6(b) shows the reduction of impact pressure compared to the same test with water-air at high-filling levels.

At the low-filling level, however, the tests indicated there was little pressure reduction as can be seen in Figure 6(a). At this filling level a significant impact can occur even when the angle between the wave front of the progressive wave and the tank wall is higher than 10 degrees. In this case, little if any gas can be trapped between the wave front and the tank wall. Significant pressure reduction that occurred at the high-filling level due to the cushioning may not happen in this case. As a result, ABS proposes a different calibration factor may be appropriate for low-filling levels.

The calibration law for the low-filling level case and the commonly used calibration law for the high-filling level case have been used to calibrate the pressure scheme for a numerical simulation tool for LNG sloshing, ABS SLOFE.
ABS SLOFE has been used to predict the sloshing pressure on the insulation system. A spatially-averaged pressure, rather than point pressure, is used as a calibration process to take account of the effect of gas cushioning in the LNG tank. The spatial average is made over areas with prescribed size. The size of the area is determined such that the averaged pressure over the area is the same as the pressure that caused damage to the insulation system. Two previous damage cases at high- and low-filling levels [5,6] have been used for the pressure calibration.

The ABS sloshing simulation program SLOFE properly predicted a maximum sloshing pressure at 30 percent filling. From the known impact strength of the primary insulation system, the factor of safety was evaluated. The number could be much lower than the factor of safety at the high-filling level.

For the Mark III system, there are additional pressure reductions due to the corrugated surface. In the next section, the factor of safety due to the enhanced cushioning due to the corrugated surface will be addressed.

Drop tests have been performed on liquid nitrogen to evaluate the cushioning effect of the corrugated surface of the Mark III system. The impact pressure is measured on the surface of the flat and corrugated surface and compared to show the effect of the corrugation.

The resulting pressure reduction is due to the additional cushioning of the trapped gas between the corrugated tank surface. The cushioning due to corrugation is referred to as the secondary cushioning to distinguish it from the primary cushioning on the flat surface. Figure 8 shows the pressure reduction from these two cushioning effects.

By considering this additional pressure reduction in addition to the factor of safety obtained without the corrugation, the Mark III system should be acceptable to the impact load at low filling level. However, it should be noted that one critical factor is missing in the drop test. The incidence angle of the insulation surface to the liquid surface had been maintained under 6 degrees in the experiment. This condition is only applicable to the sloshing impact at high-filling levels where the impact occurs at the crest of the standing wave hitting the tank top.

The cushioning factor obtained in the drop test experiments can be applied to the Mark III system if the filling level is restricted to high filling (0.95H and above). However, for a partial filling level lower than 0.75H, the cushioning factor at incident angles greater than 6 degrees should also be studied. At the filling level 0.5H ~ 0.7H, the maximum impact pressure is observed at the knuckle of the upper chamfer, where the incident angle could be greater than 45 degrees. At the filling level lower than 0.3H, the maximum impact pressure is observed acting on the bulkheads at about the same height as the filling level. The impact is due to the collision of the hydraulic jump with the bulkhead. The numerical simulation using SLOFE showed that the angle between the wave front of the hydraulic jump and wall is 10 to 20 degrees. The angle was 11 degrees for the severest sloshing impact.

Assessment of Tank Structure

Fig. 7  Secondary cushioning due to corrugation in the Mark III system

Fig. 8  Pressure reduction due to the primary and secondary cushioning

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Fig. 10  Hydroelastic Response of Stiffened Plate in Slamming Test [7]

\[ \beta: \text{incidence angle}, \ V: \text{impact velocity} \]
\[ \sqrt{\beta}: \text{transverse girder spacing}, \ I: \text{Moment of inertia} \]
\[ E: \text{Young’s modulus}, \ \rho: \text{water density} \]
\[ \varepsilon_{\text{max}}: \text{maximum strain} \]
The cushioning factor at incident angles higher than 6 degrees has been estimated by comparing the volume of gas that can be trapped between the corrugated surface and the liquid surface.

More advanced experiments to consider the impact condition at the low-filling level are needed to establish accurate calibration factors for the impact pressure.

The impact load on the insulation system eventually transmits to the tank structure. The estimation of the impact load transmitted to the structure is important for evaluating the safety and possible need for strengthening of the plating and bulkhead stiffeners.

Dynamic structural analysis has been undertaken to estimate the transmission rate of the load. The impact load obtained from the SLOFE simulation is applied to the insulation system that is modeled by 3-D solid models. The added mass of the liquid is considered by increasing the density of the primary membrane. The stress level on the tank structure with and without the presence of the insulation system has been compared to see how much of the load is absorbed by the insulation system.

Both the plywood box and the polyurethane foam in the No. 96 and Mark III system absorb more than 70 percent of the impact load from the liquid side. In the case of the Mark III system, which is thinner than the No. 96 system, the material damping of the polyurethane foam plays an important role in the absorption of the impact load.

The dynamic analysis also provides the dynamic load factor (DLF), which is defined as the ratio of the dynamic response to the quasi-static response of the structure to the same load. It is well known that the DLF depends on the ratio between the duration of the load and the natural period of the structure.

Also important is the damping of the structure. Figure 9 shows the dynamic load factor of a simple spring-mass system with different damping ratios. DLF can be less than 1 when the impact duration is less than the natural period of the structure. The damping of the structure also affects the DLF significantly. When the damping ratio is 0.6, which is the case for the polyurethane foam, the DLF decreases to 2/3 of the undamped case.

Hydroelasticity, or the fluid-structure interaction, is another important parameter in the evaluation of the DLF. In the case of impulsive response due to sloshing or slamming impact, the most dominant effect of the fluid-structure interaction is the fluid inertial force, which can be given in terms of added mass to the structure. The added mass increases the natural period of the structure and decreases the DLF compared to the one without the presence of the fluid. Figure 10 shows the DLF based on the maximum strain on the stiffened plate in a slamming test [7]. The DLF barely exceeds 1.2.

It is also of interest to note that the DLF decreases to zero as the incidence angle decreases. This is because the impact pressure at the low incidence angle is more localized and has a shorter duration, as observed in the sloshing at the high-filling condition.

The DLF obtained from the dynamic analysis is used to evaluate the static equivalent load on the tank structure. The estimated static load is used to develop a new sloshing formula for the

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**Analysis of Pump Tower Loads**

The pump tower provides structural support for the loading and discharging facilities such as pumps, pipes and level gauges in an LNG tank. The tower is located near the center of the aft transverse bulkhead in a membrane tank. It usually consists of 3 - 4 main supporting pipes and a number of bracing members that connect the main pipes for structural integrity.

The hydrodynamic load on the pump tower, which has a similar shape to offshore jacket structures, can be effectively estimated by the Morison formula that has been widely used to obtain wave loads on offshore structures. The Morison force consists of the inertia force, which is proportional to the acceleration of the fluid particle at the location of the pump tower and the drag force that is proportional to the square of the fluid velocity.

Experiment and numerical simulation has determined that the sloshing motion in LNG tanks at high and low filling levels shows different features. At the high filling level, where the filling height is more than 90 percent of the tank height, the standing wave motion is observed in the tank. Since the amplitude of the wave is restricted by the gap between the liquid level and the tank top, there is no significant liquid motion inside the liquid domain.

However, near the top of the tank, the interaction between the standing wave and tank top generates a rapid change of the fluid velocity, which results in a large acceleration of the fluid particle. As a result, an inertia-dominant Morison force, highly concentrated at the top of the tank and with short duration, is observed in the experiment and numerical simulation, as depicted in Figure 12(a).

At the low filling level, where the filling height is less than 20 percent of tank width (for lateral motion) or length (for longitudinal motion), hydraulic jump or bore can be found in the tank. As the liquid velocity in the tank increases the drag force increases rapidly; the drag force is proportional to the square of the fluid velocity.
The numerical simulation shows that the magnitude of the drag force at the low filling level is much higher than the inertia force at the high filling level. The magnitude of total force at this lower filling level can reach tens of tons, which may cause structural damage to the pump tower. The drag force is concentrated at the bottom of the pump tower, which may result in a significant load on the connecting structure to the hull at the tank bottom.

Once the sloshing load on the pump tower is calculated, the instantaneous load at the moment of maximum total force is taken as the input for the structural analysis. For the final structural analysis the combination of the following loads are considered:

- Sloshing load
- Thermal load
- Inertial load due to ship motion and acceleration

The instantaneous sloshing load is combined with the thermal load due to the temperature drop caused by the LNG and the inertial load due to the ship motion. The load due to the inclination of the tank by roll or pitch motion is also included in the inertial load.

The stress on the pump tower structure due to this combined load is calculated from the static analysis by NASTRAN. As the acceptance criteria, unity checks by the American Petroleum Institute (API- RP-2A-WSD) code are made to check the column buckling due to combined loading for the bracing members and the punching shear for the connections.

CONCLUSIONS

An analysis method to assess the strength of the insulation system, tank structure and pump tower for membrane LNG tanks has been presented. There are concerns regarding the new operating requirements for partial loads especially at low fillings of 30 percent. Some findings of the sloshing analysis at the low-filling conditions are:

- Sloshing impact pressure is higher than the high-filling level condition
- Strengthening of the bulkhead scantling may be necessary, especially at the lower part of the structure
- Design loading of the lower part of the pump tower and its connecting structure to the hull is much higher than in the high-filling level condition.

Figure 13 shows a typical stress distribution at the 30 percent filling case, where the pump tower load is at a maximum. The upper and lower portions of the tower are highly stressed due to the thermal and sloshing load, respectively. In this case, some bracing members in the pump tower structure would require strengthening to withstand the higher loads at the low filling level.

The load on the pump tower is also transmitted to the hull structure. In the case of a 30 percent filling level, 70 percent of the load is transmitted to the bottom structure of the hull. At the 80 percent filling level, 75 percent of the total load is transmitted to the trunk deck (or inner deck in old designs). The structure of these connecting areas has to be designed accordingly.

Besides the sloshing and thermal load, the vibration and fatigue life of the pump tower should also be examined.
The evaluation of the safety factor of the insulation system still demands more careful assessment of the impact strength of the containment system and the scale law relating model impact pressure to full-scale. The following recommendations are proposed to improve the evaluation:

- The current scale law for sloshing impact pressure works well at the high-filling level
- A different scale law for the sloshing impact pressure should be used at the low-filling level
- More advanced model testing to study the low-filling conditions is needed
- Model testing with the correct liquid-gas density ratio is recommended
- For the Mark III system, additional drop tests to evaluate the cushioning effect at incidence angles higher than 6 degrees is needed to simulate the impact at the low-filling level

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REFERENCES


