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DYNAMIC ANALYSIS OF LIQUEFIED NATURAL GAS TANKS SEISMICLY PROTECTED WITH ENERGY DISSIPATING BASE ISOLATION SYSTEMS

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Abstract. *The time domain seismic response of a representative liquefied natural gas (LNG) tank isolated at its base level with rubber bearings is investigated. The problem is solved numerically by means of a detailed finite element model, taking into account fluid-structure interaction effects. Two types of seismic isolation systems are investigated: lead core rubber bearings and linear rubber bearings combined with non linear viscous dumpers. Both these systems are characterized by strong energy dissipation mechanisms. The isolation systems are modeled as non-linear spring-dashpot elements with properties calculated on the basis of experimental data obtained from the literature. The seismic excitation considered is an artificial accelerogram compatible with the Eurocode 8 provisions. Results concerning base shear force, sloshing vertical displacement and deflection of the inner steel container are presented. In order to measure the effectiveness of the isolation systems, percentage reductions of the peak response of all mentioned quantities are calculated using the non-isolated tank as reference.*

1 INTRODUCTION

Natural gas is a fossil fuel (90% or more methane) that is usually transported at its gaseous state through ducts from the production site to the place of its consumption. Alternatively it is possible to cool the product down to -170 ^{0}C so that it condenses to its liquid state. In that way the density of the product increases by approximately 600 times making it possible to ship it in specially designed vessels and store it in thermally insulated tanks. The stored product can then be re-evaporated in appropriate facilities and piped to the consumption. The facilities related to the unloading, storage and re-vaporisation of the Liquefied Natural Gas (LNG) are located in the same site which is usually called an LNG terminal.

LNG terminals are crucial facilities for a natural gas distribution system because, besides providing a backup in natural gas supply, they balance the difference between the demand, which varies constantly, and the supply from the international ducts, which is essentially constant. Because of the importance of the LNG tanks, very sever requirements are imposed concerning the ability of LNG tanks to withstand several postulated accidental actions such as aircraft impact, explosion, fire, major leak and earthquake. Especially for the earthquake action, LNG tanks are expected to sustain a major seismic event, of a return period of over 5000 years, up to 10000 years, without undergoing catastrophic damage, while being able to remain fully operational during a medium seismic event of a return period of around 500 years. Design issues for LNG tanks can be found in several specialized publications, e.g. Bomhard and Stempiniewski [1] and Tajirian [2].

The modern aseismic design of LNG tanks is based on base isolation and energy dissipation techniques. The seismic protection devices usually implemented in LNG tanks are either rubber-type bearings [4,2], such as lead core rubber bearings and high damping rubber bearings, or sliding-type bearings such as the friction pendulum bearings [5,2]. All the above systems feature main functions: detaching the structure from its foundation, ensuring the necessary restoring force and providing energy dissipation. Alternatively, separate energy dissipation devices can be used in combination with linear rubber bearings. The function of these devices is based either on the hysteretic behaviour of a metal or on the viscous behaviour of a fluid.

In this work, two base isolation systems, i.e., lead core rubber bearings [6] and linear rubber bearings combined with non-linear viscous dampers, are investigated numerically using the finite element method (FEM). Rubber bearings are formed by alternating layers of hot vulcanized elastomer and steel shims. The elastomer layers provide the horizontal flexibility required for the decoupling of the horizontal structural motion from the ground motion, while the steel shims ensure adequate vertical stiffness. In the case of lead core rubber bearings absorption of energy is achieved through yielding of a lead prismatic core placed in the center of the bearing. In the case of non-linear viscous dampers the energy is absorbed during the movement of a piston in a chamber filled with viscous fluid. Selective results concerning base shear force, sloshing and deflection of the inner steel container are presented.

2 DESCRIPTION AND MODELING OF LNG TANKS

A LNG storage tank has several functions related to the safe-keeping of its content: a) keeping the content from escaping to the environment, b) preventing the atmospheric air from entering the tank, c) defending the content against the effects of external events including accidents such as earthquake, fire and explosion d) maintaining the appropriate conditions in the tank particularly in respect of temperature and pressure (slightly above atmospheric). To achieve these conditions LNG tanks are usually configured as a double shell, as shown in Fig.

1. Thus, they are constituted of an outer prestressed concrete cylindrical shell which is capped by a spherical reinforced concrete dome and an inner steel cylindrical shell open at the top and closed at the bottom by a steel plate. In general the capacity of LNG tanks ranges between 50000 m^3 and 250000 m^3 with values around 150000 m^3 being the most preferable nowadays. The height to radius ("slenderness") ratio ranges from around 0.5 to around 1.5. Ratios higher than 1 allow a better use of the available land but their seismic behavior demonstrates obvious disadvantages. This is, however, what makes them good candidates for the implementation of seismic protection systems. Thus, for the "slender" tank studied in this work, the height to radius ratio is about 1.5. The inner tank height is 36.82m and its radius is 23.60m, while the outer tank height is 39.95m, and its inner radius is 24.48m. The maximum height of the liquid volume is 36.39m. The outer shell is of constant thickness 0.8m along its height, while the thickness of the inner shell increases from top to bottom from 8.0 to 25.5mm. The space between the two shells is filled with perlite to insure proper thermal insulation of the content. The outer shell seats directly on a circular foundation slab, while between the bottom of the inner container and the foundation slab there is a layer of foam glass (0.85m) for thermal insulation purposes

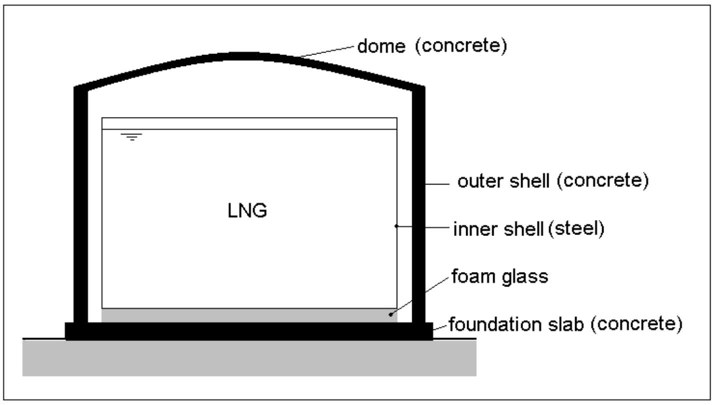

Figure 1: General configuration of an LNG tank with double shell

The seismic analysis of the selected LNG tank is performed by means of the ANSYS finite element program [8]. The outer and the inner shell as well as the dome and the foundation slab are modeled by four-nodded, 24 DOF quadrilateral shell elements. The foam glass layer is modeled by eight-nodded 24 DOF solid elements. The fluid content is modeled by eight-nodded 24 DOF fluid elements. The fluid-structure interaction is approximated by prescribing appropriate coupling equations at the nodal points on the fluid-structure interface.

3 PRELIMINARY DESIGN AND MODELING OF THE ISOLATION SYSTEMS

Both seismic isolation systems under consideration are assumed to comprise a number of similar rubber bearings, or bearings combined with dampers, uniformly distributed under the base slab. The total number of required bearings is derived from the assumption that a single bearing supports approximately 10-12 m^2 of foundation slab, at maximum. Thus, approximately 190 bearings should be used for the tank under consideration. In general dampers must be placed in two directions. The number of dampers can thus be assumed equal to double the number of bearings, though this is not necessary.

Two major assumptions are inherent in the modeling of the seismic isolation systems analyzed in the present study. The first is that the forces applied from the devices to the base slab are uniformly distributed on the entire area of the slab. The second is that the in-plane stiffness of the slab is infinite. Following these assumptions, the vertical stiffness of the bearings is simulated using Winckler type plate elements [8,9], with an appropriate foundation coefficient, while the horizontal reaction of the bearings and of the dampers is simulated using a single non-linear spring – dashpot element connected to the centre of the slab (dampers are assumed to act only in the direction of the excitation). This model for the base isolation system is illustrated in Figure 2

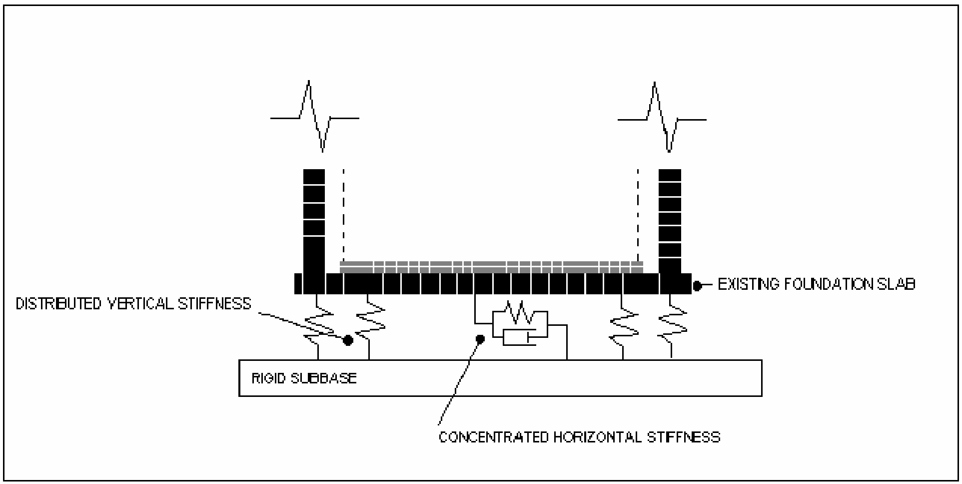

Figure 2: Modeling of the isolation systems

3.1 Vertical stiffness

The Winckler model requires the determination of the elastic foundation stiffness (EFS), which is defined as the pressure required to produce a unit normal deflection of the foundation and is given as

$$EFS = \frac{N * K_v}{A_s} \tag{1}$$

where N is the number of the installed isolators, K_v the vertical stiffness of each isolator and A_s the area of the base slab.

3.2 Horizontal stiffness of lead core rubber bearings

For isolated structures, a fundamental period, i.e. the natural period of the structure moving as an almost rigid body on the isolators, is usually selected in the range of 1.5 to 3 sec. For this study, a fundamental period of 2sec is chosen. Given the total mass M of the structure, the total horizontal stiffness K of an equivalent elastic isolation system, that would lead to a fundamental period of 2 sec, can be approximately evaluated on the assumption of an equivalent single degree of freedom system as

$$K_{eq} = 4 \cdot \pi^2 \cdot M / T^2 \tag{2}$$

The horizontal stiffness of a set of lead core rubber bearings is simulated by a bilinear elastoplastic model, as shown in Figure 4. The assumptions related to the preliminary design of the isolation system are: (a) δ_{max}=0.18 m, (b) λ=K_{el}/K_{pl}=11, and (c) ξ =40% which is reasonable for structures isolated with lead core rubber bearings [11].

The assumptions (a) and (b) made for the case of lead core rubber bearings for the determination of the parameters of the applied model, can be also employed in the case of lead core rubber bearings, where the following relationships are also used:

$$K_{eq} \cdot \delta_{\max} = K_{el} \cdot dp + K_{pl} \cdot dl \tag{3a}$$

$$dp + dl = \delta_{\max} \tag{3b}$$

$$4dp \;\; K_{el} - K_{pl} \;\;\; \delta_{\max} - dp \;\; - 2 \cdot \pi \cdot \xi \cdot K_{eq} \cdot \delta_{\max}^{2} = 0 \tag{3c}$$

$$F_y = K_{el} \cdot dp \tag{3d}$$

After computing the various unknown variables appearing in Eqs (3), the bilinear model of Figure (4) is implemented in the finite element model as the force-displacement relationship of a non-linear spring element connected to the centre of the foundation slab.

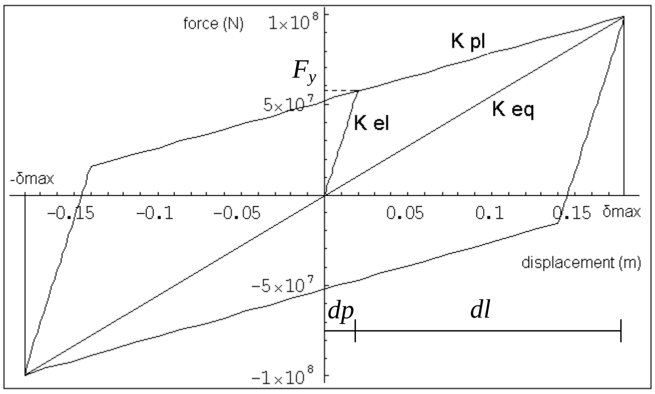

Figure 3: Energy dissipation loop for the set of lead core rubber bearings used in this work

The parameters corresponding to the model of the particular isolation system used in this work, are $K_{el} = 37.95*10^8$ N/m, $K_{pl} = 3.45*10^8$ N/m, $f_y=2.97*10^7$ N.

3.3 Horizontal reaction of linear bearings in combination with non linear viscous dampers

In the case of linear bearings the horizontal stiffness of the seismic isolation stiffness that leads to a fundamental period of T = 2 sec for a full tank is easily determined from the equation

$$Kel = 4\pi^2 (m-m_c)/T \tag{4}$$

where m is the total mass of the structure and m_c is the convective (“sloshing”) mass of the liquid. The convective mass is subtracted from the total mass because it oscillates in a mode with a period much larger than the fundamental period of the isolated structure and, for this reason, is considered uncoupled from the fundamental mode of the isolated structure

In the case of application of non-linear viscous dampers the reaction force of the system is given by

$$F_d = C_{nl} v^{0.15} \tag{5}$$

where v is the velocity of the base and C_{nl} is the constant of the non linear damper system. In this work, the constants of the spring-dashpot element concentrated at the center of the slab are: $K = 5.55*10^8$ N/m, $C_{nl} = 5.25*10^7$ Nsec/m.

4 NUMERICAL RESULTS AND DISCUSSION

Time domain non-linear dynamic analyses are preformed with non-linearities concentrated at the spring simulating the isolation system. The linear acceleration method is used for the integration of the system of equations of motion while the full Newton-Raphson method is used for the solution of the non-linear systems of equations. An artificial accelerogram compatible with the EC-8 spectrum for soil type C is used as an input excitation.

In the following, selective results of the analyses of both systems investigated in this work are presented ("lrb" stands for lead core rubber bearings and "nlv" stands for non-lenear viscous dampers). In Figure 4, the base shear force below the foundation slab versus the corresponding base displacement is plotted for each isolation case. In Figure 5, the total base shear force just above the foundation slab is plotted versus time. For comparison purposes the base shear time history for the non-isolated case (fixed base conditions), is also shown. In Figure 6, time histories of base displacement are plotted for each isolation case. The time history of the horizontal displacement, relative to the base, of the inner shell at the fluid free surface level is plotted versus time in Figure 7. For comparison purposes, the horizontal displacement of the inner shell for non-isolated (fixed base conditions) is also shown. Similarly, in Figure 8 the relative displacement at 2/3 of the height of the inner shell, where the maximum deflection is observed, is illustrated. Finally, in Figure 9 the wave height at the intersection of the fluid free surface and the inner shell is plotted versus time for each isolation case and, for comparison purposes, the fixed base conditions.

From the exhibited results the following conclusions could be made: (a) in terms of base shear force, percentage reduction factors of the order of 70% are calculated for both isolation systems investigated in the present work, (b) maximum stresses in the inner shell are reduced by approximately 60%, in comparison to the non-isolated case where fixed base conditions are considered, and (c) the sloshing height remains practically unchanged in comparison to the non isolated tank.

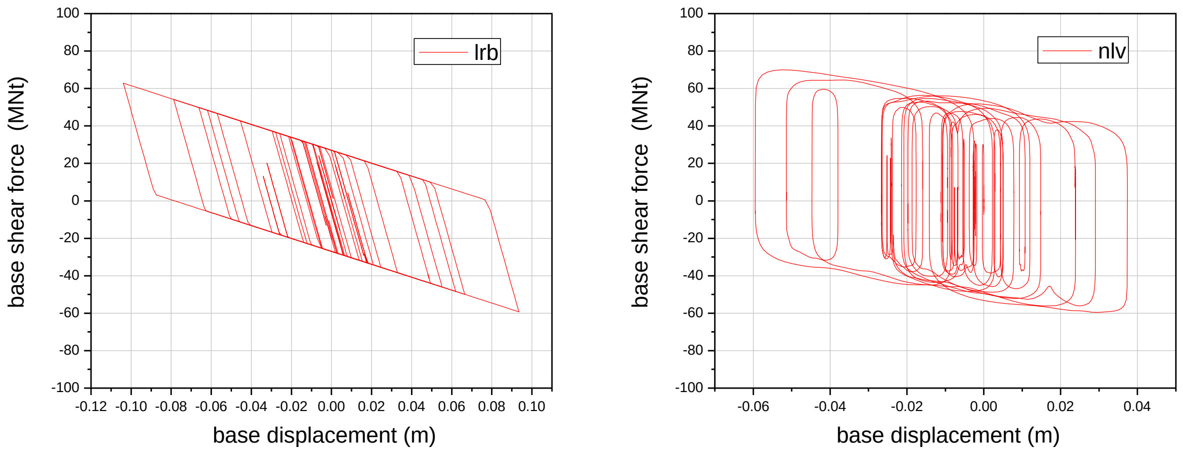

Figure 4: Base shear force below the foundation slab versus base displacement for each isolation case ("lrb" stands for lead core rubber bearings, "nlv" stands for non-linear viscous dampers)

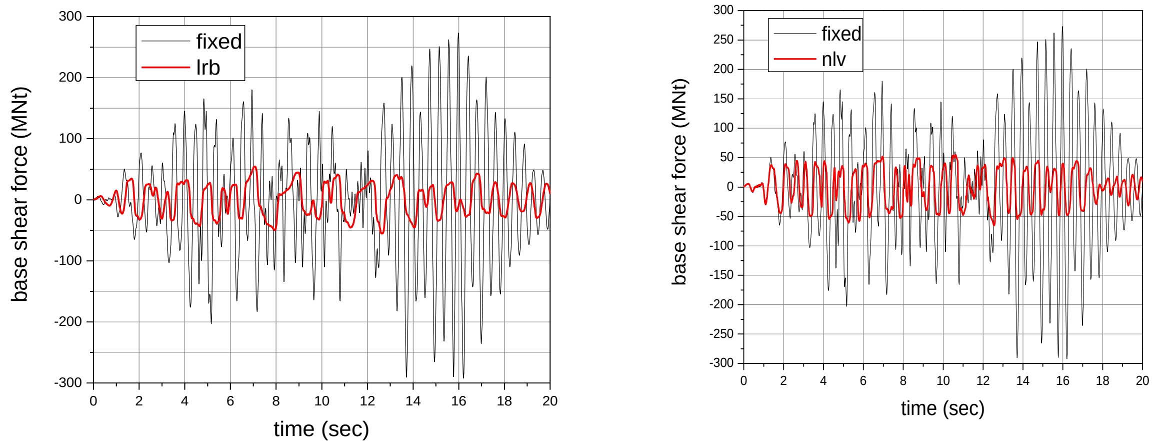

Figure 5: Time histories of total base shear just above the foundation slab for the isolated and the non-isolated (fixed base conditions) cases.

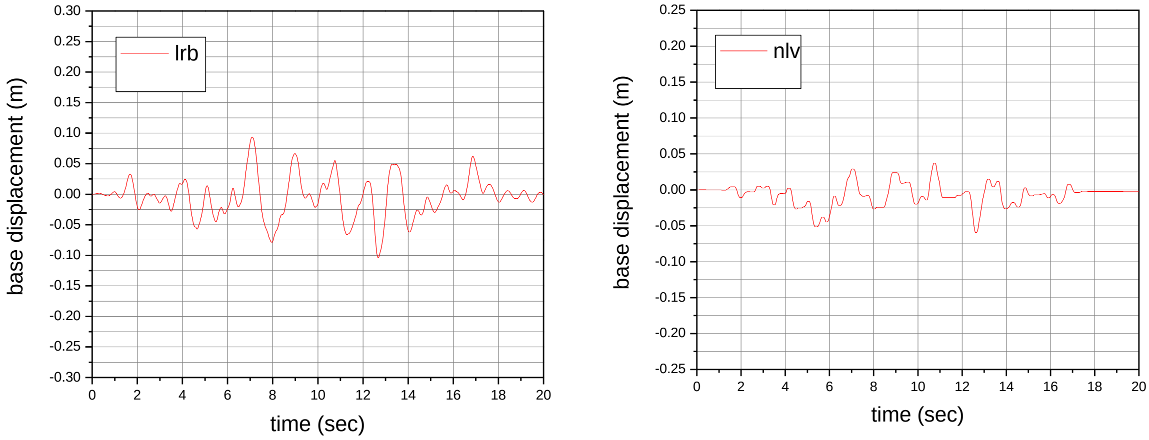

Figure 6: Base displacement time histories for each isolation case

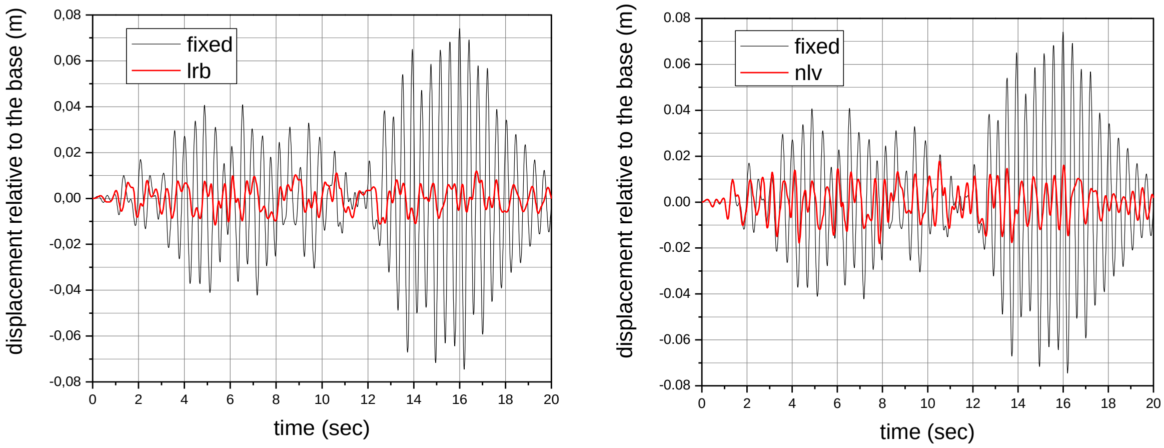

Figure 7: Time histories of the relative to the base displacement of the inner shell at the fluid free surface level

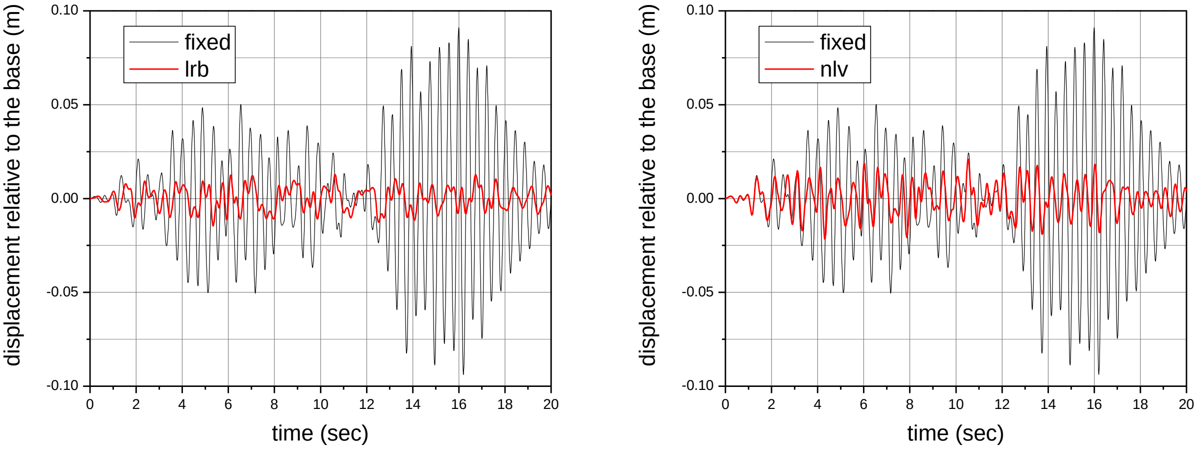

Figure 8: Time histories of the relative to the base displacement of the inner shell at 2/3 of its height

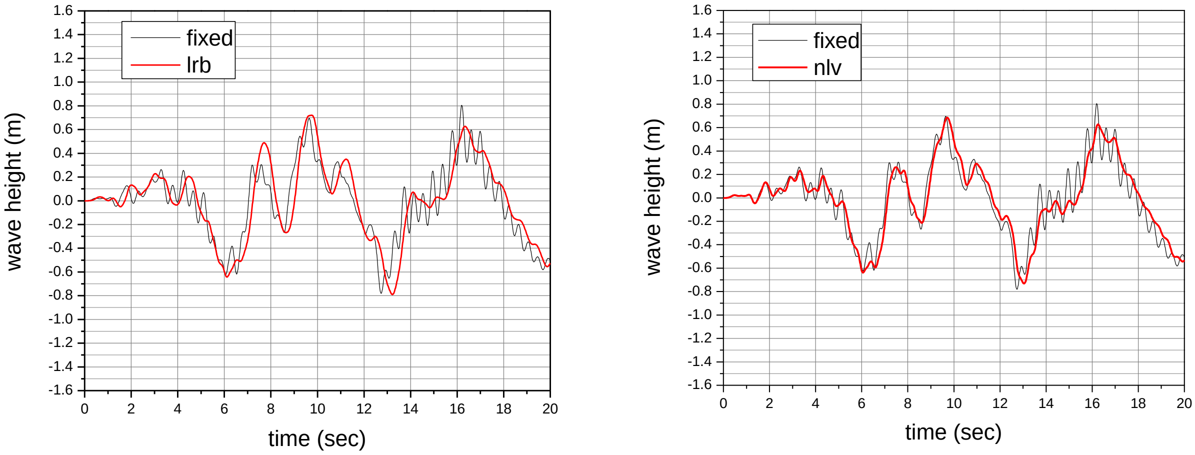

Figure 9 : Wave height time histories at the intersection of the fluid free surface and the inner shell

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REFERENCES

[1] Bomhard, H. and Stempniewski, L (1993) “LNG Tanks for seismically highly affected sites,” *Intl. Post-SMiRT Conference Seminar on Isolation, Energy Dissipation and Control of Vibrations of Structures*, Capri, Italy.

[2] Tajirian, F. F. (1998) “Base isolation design for civil components and civil structures,” *Proceedings of the Structural Engineers World Conference*, San Francisco, California, July.

[3] Buckle, I. G. and Mayes R. L. (1990) “Seismic Isolation History, Application, and Performance - a World View,” Earthquake Spectra 6(2), 161-201.

[4] Tajirian, F. F. (1993) “Seismic isolation of critical components and tanks,” *Proceedings of the ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control*, San Francisco, California, pp. 233-244.

[5] Zayas, V. A. and Low D.S. (1995) “Application of seismic isolation to industrial tanks,” *Proceedings of the ASME/JSME Pressure Vessels and Pipe Conference*, Hawaii, PVP-Vol 319, pp. 273-244.

[6] Soong, T. T. and M. C. Constantinou, eds. (1994), *Passive and Active Structural Control in Civil Engineering, CISM Courses and Lectures No. 345*, Springer-Verlag, Wien-NewYork.

[7] European Committee for Standardisation (2002), *Eurocode 8 European Standard. Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings*, ENV1998-1-1.

[8] Swanson Analysis Systems, Inc. ANSYS (1992), *User’s Manual for Revision 5.0, Procedures*. Houston, PA.

[9] Anil K. Chopra (1995), *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, Prentice-Hall, New Jersey.

[10] Naeim, F. and Kelly, J.M. (1999), *Design of seismic isolated structures: From theory to practice*, Wiley, New York.