IMPLEMENTATION AND VALIDATION OF FINITE ELEMENT MODELS OF STEEL HYSTERETIC TORSIONAL ENERGY DISSIPATORS

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SUMMARY

In the framework of the EC-funded REEDS Project, innovative energy dissipators aimed at reducing seismic response in civil buildings and industrial plants, have been designed, manufactured and tested. This paper presents the main features of steel hysteretic torsional dampers (SHTDs) designed and manufactured by FIP Industriale. A particular application of these dampers, studied within the REEDS project, is their use as part of the base isolation system of a Liquefied Natural Gas (LNG) storage tank. A scale mock-up of such a structure (4 m diameter, 172 kN weight including 1 m level of liquid) was built by the French Bouygues Company and subjected to shake table tests. A separate paper presents the results thereof. The development of SHTDs encompassed many tests on both full scale and scaled prototypes using different shapes and materials. Test results showed optimal performance for these device; particularly, in terms of fatigue life and energy dissipation (efficiency of dissipators is larger than 70%). Another useful characteristic of said dampers is their high elastic stiffness, which makes them particularly suitable to enhance damping in many structures. For example, their insertion in bracings used to seismically protect buildings of frame-construction. Finite element models (FEMs) of SHTDs were implemented by ENEL and ENEA in the ABAQUS code. Both isotropic and cinematic hardening models were used so as to numerically reproduce the initial behaviour as well as the stabilised cycles. The FEMs were validated based on the above-mentioned experimental results.

DEVICES CONSIDERED

The innovative characteristics of the SHTDs are that the energy dissipation is based on the torsional strain of a steel bar. A connecting-rod transforms the linear displacement of the structure during the earthquake into rotational displacements. The advantages of the torsional devices with respect to the more common bending devices, is a much higher fatigue life due to a better use of the material: as a matter of facts, all the cross-sections of the torque bar are subjected exactly to the same strains and stresses. SHTDs can be used in parallel with isolation bearings to increase the energy dissipation and also inside the structure, by connecting parts of the frame in which significant relative displacements are expected during an earthquake.

Some devices with different shapes and sizes were developed and analysed within the REEDS Project [ENEL et al., 1996; Dusi et al., 1999; Martelli et al., 1999]. Initially, scaled devices, including those to be used under the LNG tank mock-up in the shaking table tests, were manufactured and tested by FIP [Castellano, 1999]. Then, a couple of full scale prototypes was manufactured by FIP and tested at ISMES lab (Figure 1), [Bergamo, 1999].

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EXPERIMENTAL TESTS

Some scaled SHTDs with different shapes and sizes were initially tested by FIP. In particular, both square (20 mm edge) and circular (20 mm diameter) cross-sections with different boundary conditions were analysed. Figure 2 shows, as an example, the fifth measured hysteresis loop for the scaled device with circular section. The large amount of energy dissipated by such a device is evident. Moreover, it is worthwhile noting that failure occurs after more than 70 cycles at quite large rotations. The circular cross-section resulted to be the most reliable, thus a couple of full scale devices with a 70 mm diameter were manufactured by FIP and tested at ISMES (Figure 1), [Bergamo, 1999].

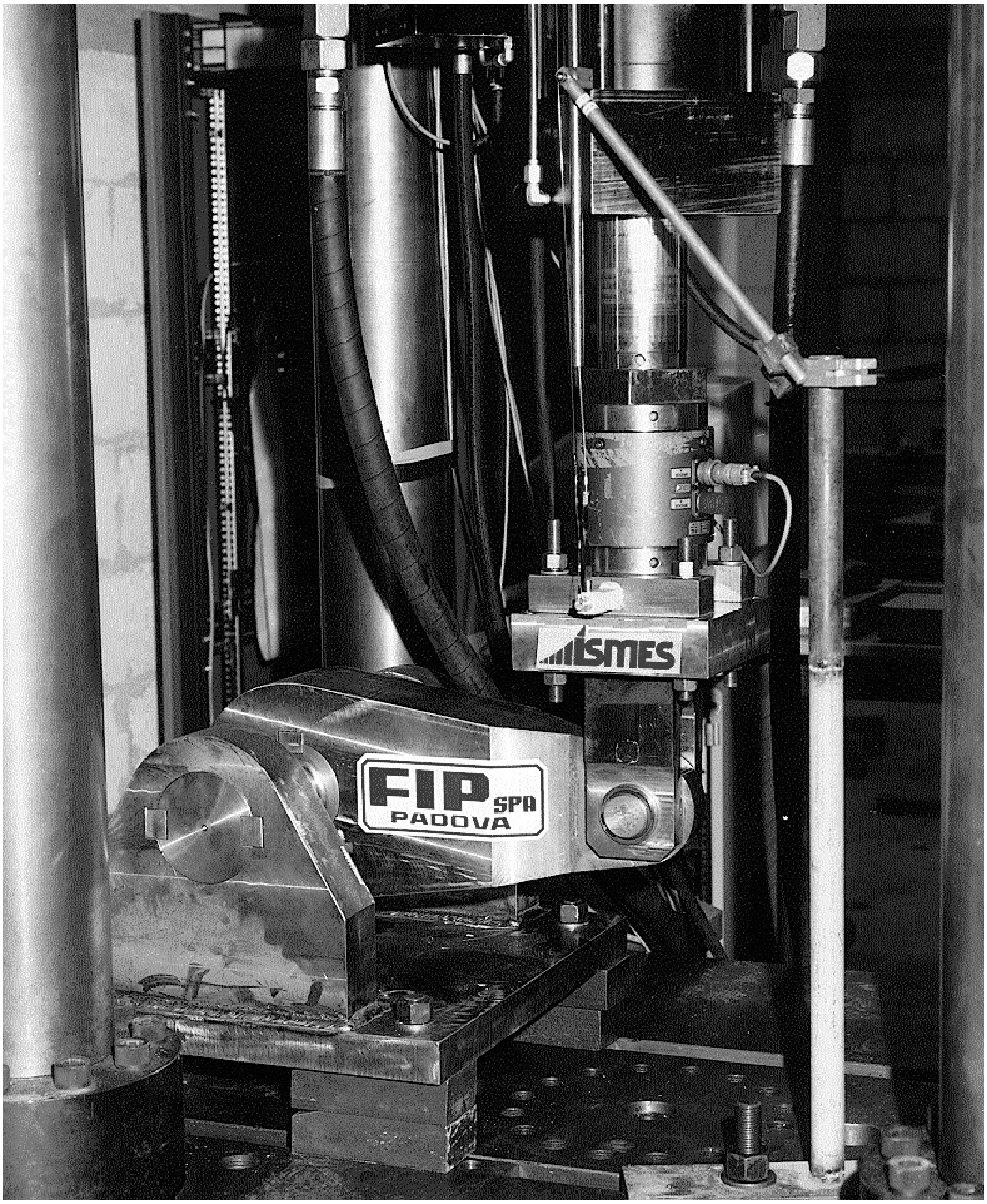


Figure 1. Full scale SHTD with tangs attachment system during the test campaign at ISMES.

Two different attachment systems were tested: the first consisted in directly welding the torque bar to the supporting structure, while the second uses steel tangs which allow for axial deformations of the torque bar

(Figure 1). Both solutions were numerically modelled and analysed (§ 3).Tests showed that the devices provide very stable hysteresis loops up to failure (which occurs after 70 cycles at about 16° rotation, corresponding to 120 mm displacement).

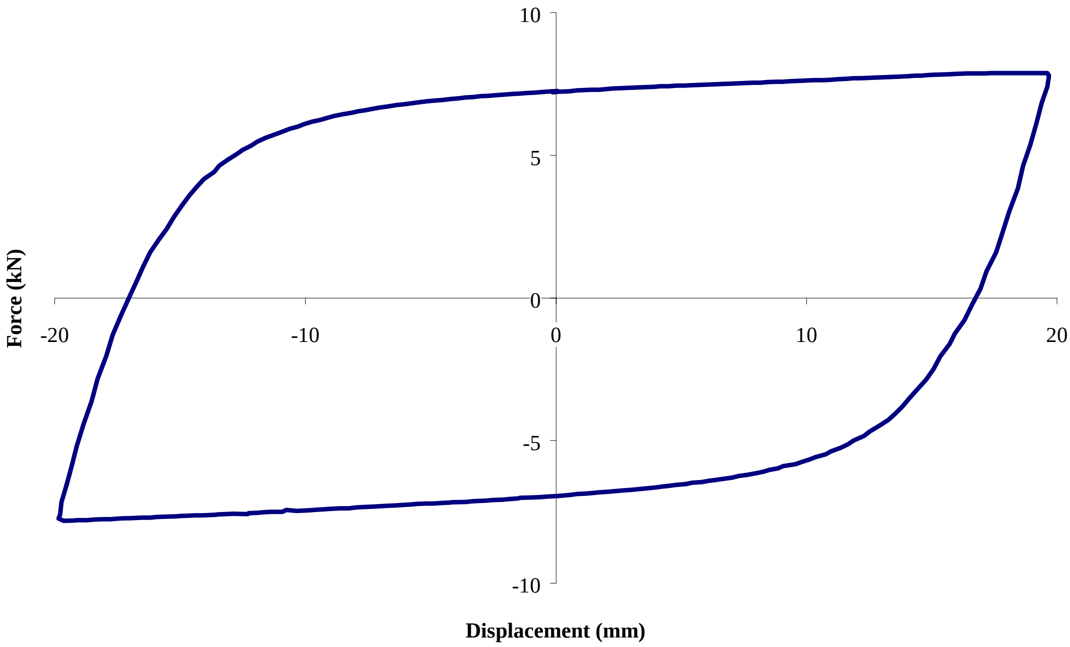


Figure 2. Measured hysteresis loop for a scaled SHTD with circular cross section

As far as the shaking table tests are concerned, several sinusoidal, random and seismic excitations were applied to the LNG mock-up (Figures 3 and 4) at the ENEA Labs of Casaccia (Rome) in December 1998, within the REEDS Project activities. The results showed the good behaviour of the SHTDs, which, coupled with elastomeric isolation bearings, provided a significant reduction of the seismic response of the LNG tank (in terms of accelerations and deformations of the tank, and sloshing motion of the water simulating liquefied gas), expecially under strong earthquakes [Castellano et al., 1999 and De Canio, 1999]. As a matter of facts, at the design displacement these devices dissipate a large amount of energy, as shown by Figure 5. More information about these tests is provided by Castellano et al., (1999), in a separate paper.

Figure 3. Seismically isolated LNG tank mock-up on the ENEA shaking table (four elastomeric bearings coupled with four SHTDs).

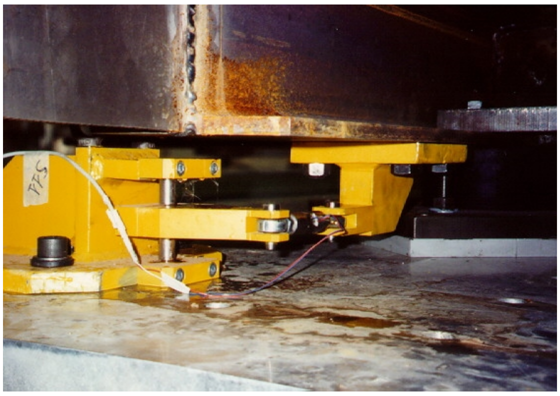


Figure 4. One of the four SHTDs under the LNG tank mock-up, coupled with elastomeric bearings, during tests at ENEA Labs.

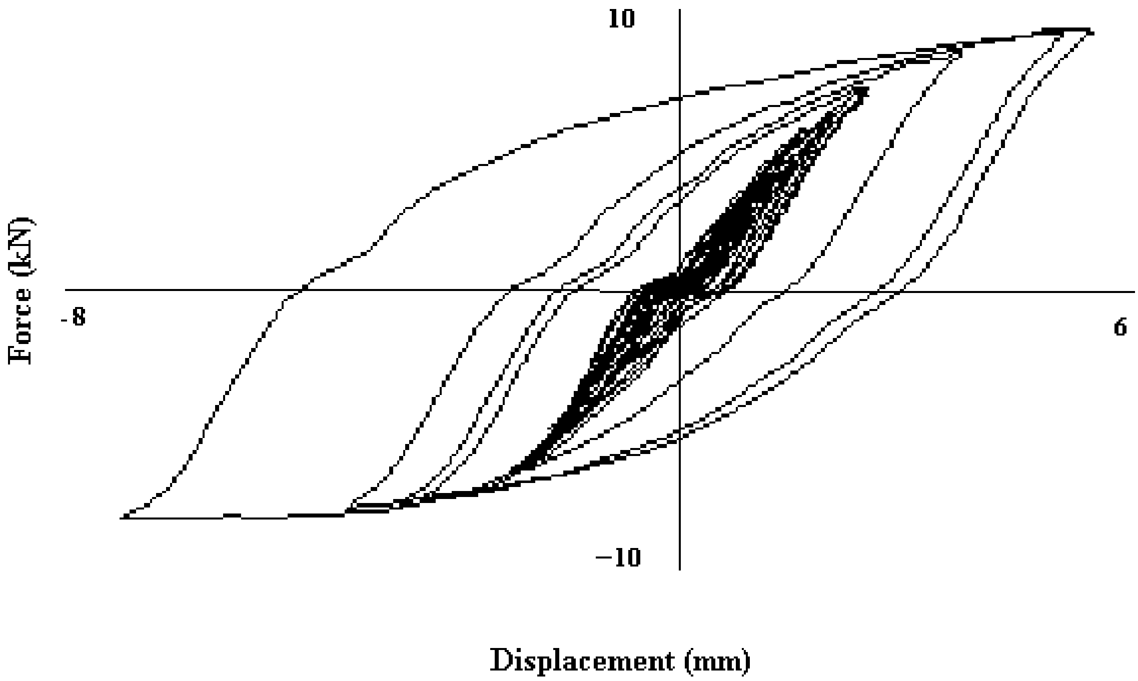


Figure 5. Hysteresis loops of one of the four SHTDs installed under the LNG tank mock-up (in parallel with four elastomeric isolation bearings) recorded during the application of a synthetic acceleration time-history generated according to Eurocode 8 for soft soils (0.3 g peak acceleration).

FINITE ELEMENT MODEL (FEM)

Several three-dimensional (3D) FEMs of SHTDs were implemented in the ABAQUS code and used for lots of parametrical analyses aimed at optimising the design of the device. Due to symmetry considerations, only half device was modelled and suitable boundary conditions were applied. As an example, Figure 6 shows the scaled SHTD with circular cross section and square ends, which had been initially manufactured by FIP. This model, which is very similar to that installed under the LNG tank mock-up, is composed by 3949 nodes and 2696 solid elements (8-nodes). The FEM of the full scale device, which consists of 3485 nodes and 2528 elements, is reported in Figure 7. Appropriate boundary conditions are applied to the model in order to correctly reproduce the two different attachment systems adopted in the tests (see § 2).

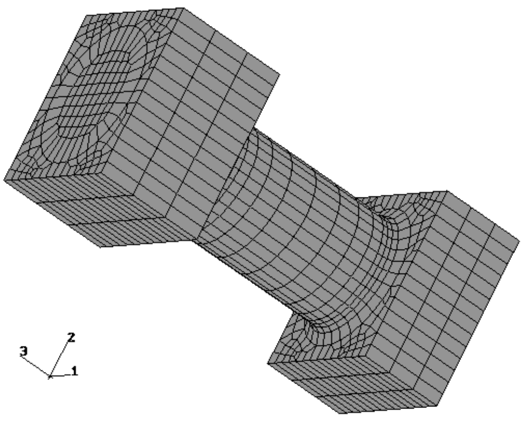


Figure 6. 3D FEM of the scaled SHTD.

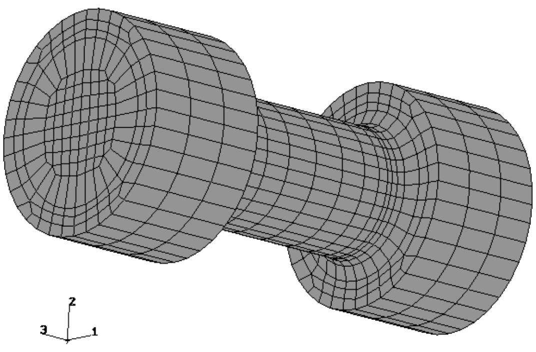


Figure 7. 3D FEM of the full scale SHTD.

NUMERICAL ANALYSIS

The elastoplastic behaviour of the SHTDs has been analysed with both isotropic and cinematic hardening. The first results to be particularly suitable for analysing the transient initial phase of the deformation while, the second well describes the stabilised cycles, which become steady after the second cycle. The definition of isotropic hardening requires as input a stress-strain curve for the steel which fully cover the range of deformations of the device. The definition of cinematic hardening is more easy and requires only two couples of stress values (and the related strains), namely the stress corresponding to the yield point and a stress value after yielding, to define the hardening rate. The elastoplastic model was initially calibrated and validated based on the results of experimental tests performed by FIP on steel hysteretic devices designed and produced by FIP for the CHIRAG off-shore platform, for which energy dissipation was based on the bending deformation of 'C shaped' steel element [Forni and Dusi, 1999; Martelli et al., 1999; Medeot and Infanti, 1997], (Figures 8 and 9).

After the calibration and validation of the elastoplastic model, the scaled SHTDs (18 mm diameter, 30 mm length) used in the above-mentioned shake table tests on LNG tank have been modelled and analysed. In particular, several parametric analyses have been carried out, aimed at defining the best shape and sizes of the device. Figure 10 shows, as an example, the FEM of the device under a rotation of 8° which corresponds to a deformation of 20 mm. Figure 11 shows the good agreement between analyses and tests, in the case of cinematic hardening. It is worthwhile noting that shaking table tests showed a great efficiency of these devices in reducing the seismic response of the LNG tank, expecially at high excitations [Castellano et al., 1999].

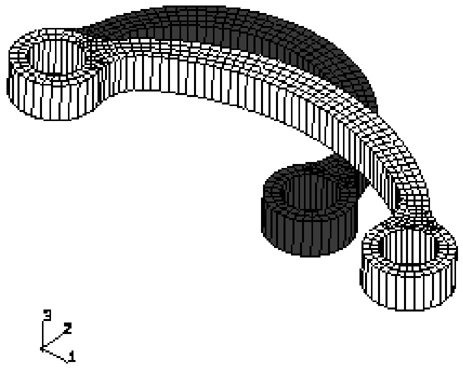


Figure 8. FEM of the CHIRAG B device at large deformations

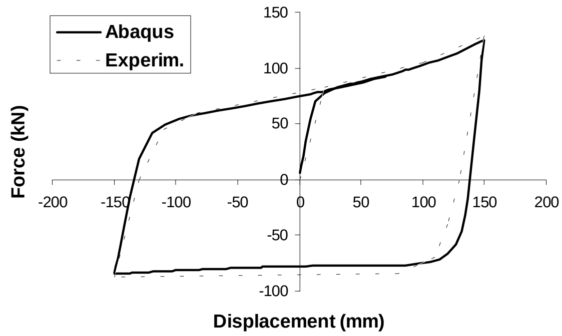


Figure 9. Measured & calculated hysteresis loops for the CHIRAG B dissipating element

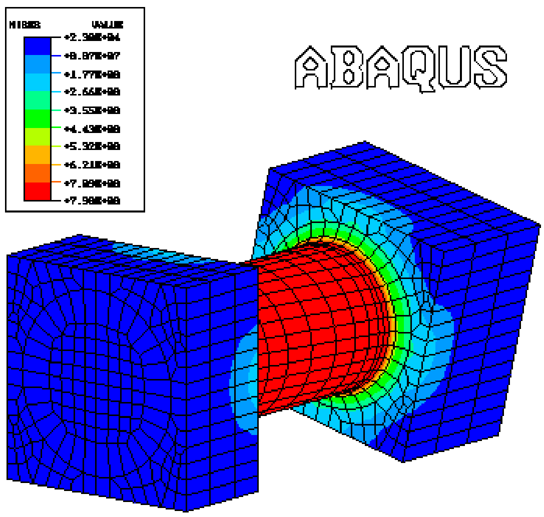


Figure 10. Von Mises distribution of the stresses in the scaled SHTD at the maximum rotation of 8°.

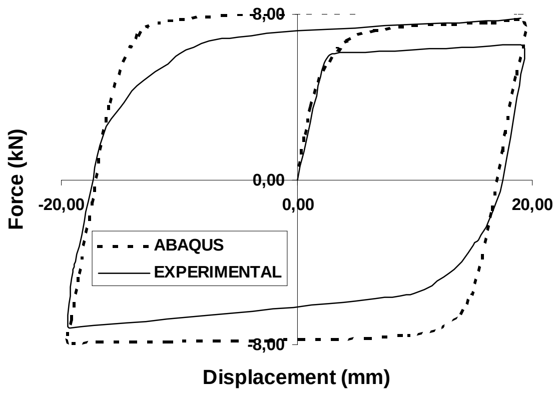


Figure 11. Measured & calculated hysteresis loops for the scaled SHTD (cinematic hardening).

Moreover, other SHTDs, characterised by different geometric features, were analysed. Figure 12 shows, as an example, a FEM of a square cross section device (20 mm side, 30 mm length), deformed to a rotation of 8°, which corresponds to a horizontal stroke of 20 mm, while Figure 13 reports the comparison between computed and experimental results in the case of isotropic hardening. Also in this case, as shown by Figure 13, the agreement between calculations and measurements is very satisfactory; this model can be easily used to optimise the design of the devices and to reduce the number of experimental tests needed for their qualification (see for instance Figure 14).

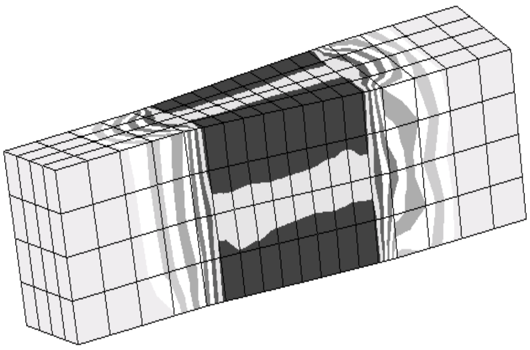


Figure 12. Von Mises stress distribution in 0 scaled SHTD (square section) at large rotations (8°)

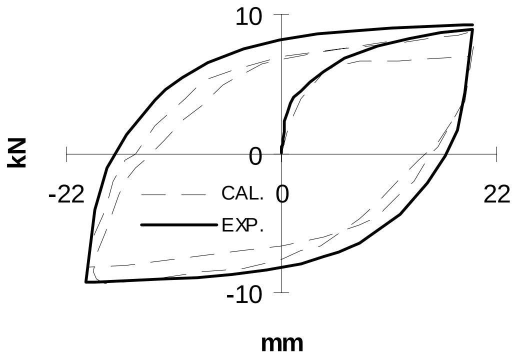
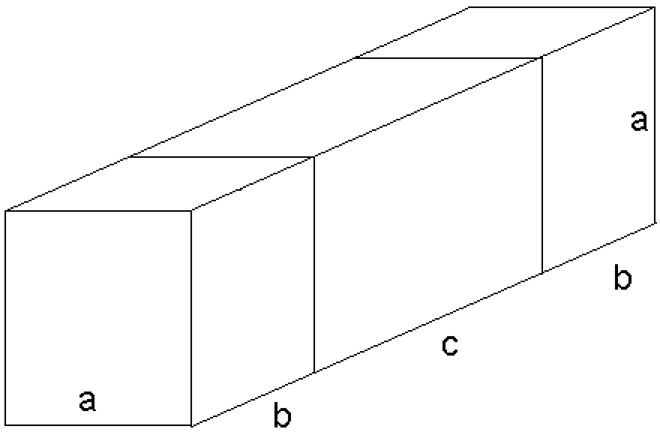


Figure 13. Measured & calculated hysteresis loops for a scaled SHTD (square section)



GEOMETRIC PARAMETERS	STIFFNESS
Reference case	1
a-30%	0.3
a+30%	2.23
b-30%	1
b +30%	1
c-30%	1.2
c+30%	0.8

Figure 14. Parametrical analyses on the square cross-section torsional device

Finally, the full scale SHTD (70 mm diameter, Figure 1) was analysed based on the results of the tests carried out at ISMES [Bergamo, 1999]. These analyses confirmed the reliability of the numerical model implemented and validated above. Figures 15 and 16 show the case of the full scale device tested at increasing amplitudes starting from 10 mm, using the isotropic hardening model. It was confirmed, in agreement with the results of the analyses on the CHIRAG device, that isotropic hardening should be used to reproduce the initial part of the hysteresis loop (see also Figure 17), while, for reproducing the stabilised cycles of the devices (Figure 18), cinematic hardening is sufficient. Particular attention must be paid to the boundary conditions for reproducing the attachment system of the torque bar to the device: as a matter of facts, when using tangs (Figures 17), the axial deformation of the torque bar must be allowed.

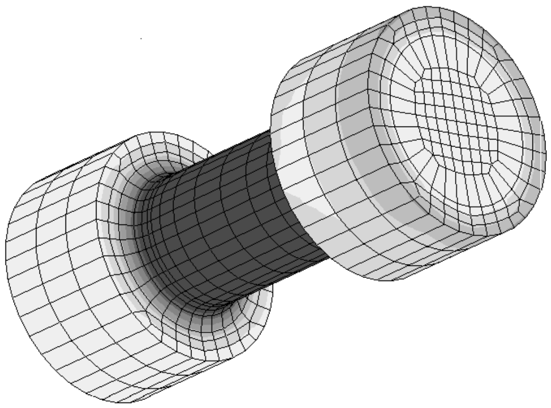


Figure 15. FEM of the full-scale SHTD designed for the LNG tank (stress distribution at large rotations)

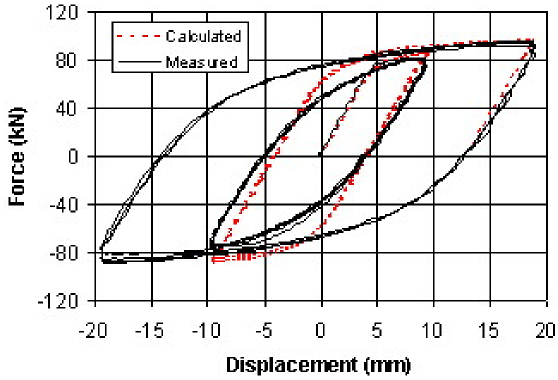


Figure 16. Comparison between measured and calculated hysteresis loops for the full scale SHTD (isotropic hardening).

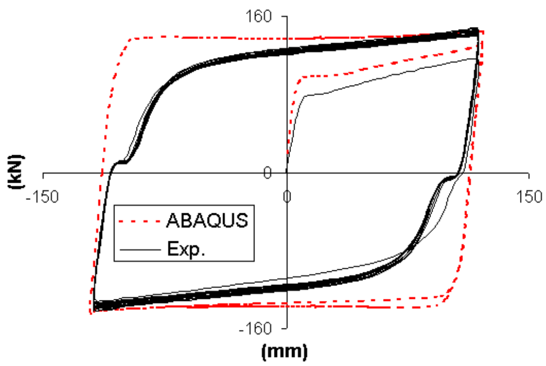


Figure 17. Comparison between measured and calculated hysteresis loops for the full scale SHTD at 16° rotation (120 mm displacement): isotropic hardening.

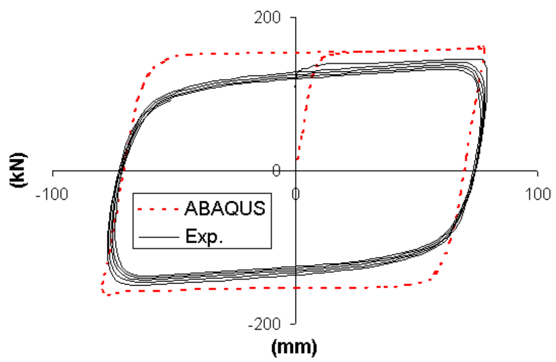


Figure 18. Comparison between measured and calculated hysteresis loops for the full scale SHTD at 11° rotation (80 mm displacement): cinematic hardening.

In the framework of the numerical activities of the REEDS project, several finite element models of steel hysteretic torsional dampers were implemented and validated based on the results of dynamic tests on scaled devices, full-scale prototypes and shaking table seismic tests on a LNG mock-up. The results of the analyses demonstrated the reliability of the numerical models, provided that the stress-strain characteristics of the steel used as input, fully cover the deformation range of the devices. Isotropic and cinematic hardening laws may be used for reproducing the initial behaviour and the stabilised cycles of the devices, respectively. Thus, finite element models of these devices can be successfully used by the designers to evaluate the effects of geometrical, mechanical and physical parameters with the aim of optimising the design, increasing performances and reducing the number of qualification tests.

CONCLUSIONS

In the framework of the numerical activities of the REEDS project, several finite element models of steel hysteretic torsional dampers were implemented and validated based on the results of dynamic tests on scaled devices, full-scale prototypes and shaking table seismic tests on a LNG mock-up. The results of the analyses demonstrated the reliability of the numerical models, provided that the stress-strain characteristics of the steel used as input, fully cover the deformation range of the devices. Isotropic and cinematic hardening laws may be used for reproducing the initial behaviour and the stabilised cycles of the devices, respectively. Thus, finite element models of these devices can be successfully used by the designers to evaluate the effects of geometrical, mechanical and physical parameters with the aim of optimising the design, increasing performances and reducing the number of qualification tests.

REFERENCES

Bergamo, G., 1999, REEDS Project, Task 7, Tests on elastoplastic devices, REEDS Report B3IS0707, 1999.

Castellano, M.G., Infanti, S., Dumoulin, C., Ducoup, L., De Canio, G., Forni, M., Martelli., A., Dusi, A., 1999, Shake Table Tests on a Liquefied Natural Gas Tank Mock-up Seismically Protected with Elastomeric Isolators and Steel Hysteretic Torsional Dampers, 12th WCEE, Auckland, New Zealand, 30 January - 4 February, 2000.

De Canio, G., 1999, REEDS Project, Task 8, LNG tank mock-up seismic tests final report, REEDS/ENEA-INN/TLB-99-001.

Dusi, A., Fuller, K.N.G., et al., 1999, Optimization of Elastic-Plastic Dampers, Viscous Dampers and Shock Transmitters in the Framework of the EC-Funded REEDS Project, International Post-SMiRT 15 Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibration of Structures, Cheju, Korea, August 23 to 25, 1999.

ENEL, ALGA, BOUYGUES, ENEA, FIP Industriale, GA, ISMES, IST, LIN, JRC, and TARRC/MRPRA, 1996, REEDS: Optimisation of Energy Dissipation Devices, Rolling Systems and Hydraulic Couplers for Reducing Seismic Risk to Structures and Industrial Facilities, EC Contract BRPR-CT96-0141, Project BEE1031, Bruxelles, Belgium.

Forni, M., Dusi, A., 1999, REEDS Project, Task 9, Elastic-plastic devices, REEDS Report B3EA0902.

Martelli, A., Forni, M., et al., 1999, New Activities Performed in Italy on Innovative Anti-Seismic Techniques for Civil and Industrial Structures, 1999 ASME-PVP Conference, 11th Int. Symposium on Seismic, Shock and Vibration Isolation., August 1-5, 1999, Boston, Massachusetts, USA.

Medeot, R., Infanti, S., 1997, Seismic Retrofit of Chirag 1 Offshore Platform, International Post-SMiRT 14 Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibration of Structures, Taormina, Italy, August 25 to 27, 1997.