“ENSSTRAM”

Title: ENSSTRAM – Novel design concepts for ENergy related Steel STRuctures using Advanced Materials
Fund: General Secretariat for Research and Technology (Aristeia II - 4916)
Partners: National Technical University of Athens (NTUA), University of Patras (UP)
Coordinator: Prof. C. Gantes (NTUA)
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Duration: 14/2/2014 - 31/10/2015
Budget: 296,000.00 €

Summary

Novel design concepts for two energy-related steel structures, wind-turbine towers and buried pipelines, have been investigated experimentally and numerically. Both types of structures play a vital role for satisfying societal energy needs and their safe and efficient design offers significant financial, social and environmental benefits, while their possible failure could have grave consequences. The proposed novel design concepts aim at exploiting innovative materials, combined with the traditional steel shells, thus enhancing the overall structural performance of both systems and extending their application to more extreme environmental actions.

Publications

Journals:

1. Vernardos, S. and Gantes, C.J., “Cross-Section Optimization of Sandwich-Type Cylindrical Wind Turbine Towers”, *American Journal of Engineering and Applied Sciences*, Vol. 8, Issue 4, pp. 471-480, 2015.
   doi: http://dx.doi.org/10.3844/ajeassp.2015.471.480
2. Melissianos, V.E. and Gantes, C.J., “Buckling and Post-buckling Behavior of Beams with Internal Flexible Joints Resting on Elastic Foundation Modeling Buried Pipelines”, *Structures*, Vol. 7, pp. 138–152, Aug. 2016.
   doi: http://dx.doi.org/10.1016/j.istruc.2016.06.007
3. Melissianos, V.E., Korakitis, G.P., Gantes, C.J. and Bouckovalas, G.D., “Numerical Evaluation of the Effectiveness of Flexible Joints in Buried Pipelines Subjected to Strike-Slip Fault Rupture”, *Soil Dynamics and Earthquake Engineering*, Vol. 90, pp. 395–410, Nov. 2016.
   doi: http://dx.doi.org/10.1080/15397734.2016.1165117
4. Melissianos, V.E. and Gantes, C.J., “Evaluation of Seismic Protection Methods for Buried Fuel Pipelines Subjected to Fault Rupture”, *Frontiers in Built Environment*, Vol. 2, Article 34, Nov. 2016.
   doi: http://dx.doi.org/10.3389/fbuil.2016.00034
5. Melissianos, V.E., Lignos, X.A., Bachas, K.K. and Gantes, C.J., “Experimental Investigation of Pipes with Flexible Joints under Fault Rupture”, *Journal of Constructional Steel Research*, Vol. 128, pp. 633-648, Jan. 2017.
   doi: http://dx.doi.org/10.1016/j.jcsr.2016.09.026
6. Melissianos, V.E., Vamvatsikos, D. and Gantes, C.J., “Performance-Based Assessment of Protection Measures for Buried Pipes at Strike-Slip Fault Crossings”, *Soil Dynamics and Earthquake Engineering*, under review.

Conferences:

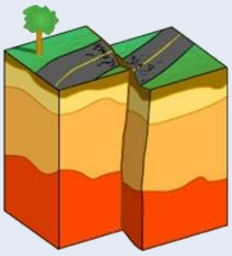
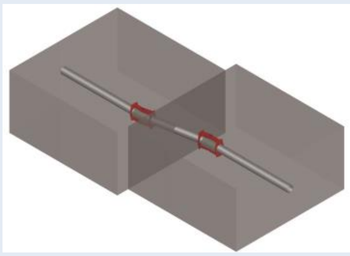
1. Melissianos, V.E. and Gantes, C.J., "Earthquake Induced Upheaval Buckling of Buried Pipelines with Flexible Joints", *2ECEES - 2nd European Conference on Earthquake Engineering and Seismology*, M.A. Ansal and M. Nurlu (eds.), Istanbul, Turkey, Aug. 25-29, 2014.
2. Karamitros, D., Zoupantis, C. and Bouckovalas, G.D., "An Analytical Method for Active Fault Verification of Buried Steel Pipelines with Bends", *2ECEES - 2nd European Conference on Earthquake Engineering and Seismology*, M.A. Ansal and M. Nurlu (eds.), Istanbul, Turkey, Aug. 25-29, 2014.
3. Melissianos, V.E. and Gantes, C.J., "Upheaval Buckling of Onshore Buried Steel Pipelines with Flexible Joints", *IASS-SLTE 2014 Symposium*, Brasilia, Brazil, Sep. 15-19, 2014.
4. Melissianos, V.E., Gantes, C.J. and Kalfantis, P.P., "Upheaval Buckling Risk Assessment of Buried Steel Pipelines due to Reverse Seismic Fault Activation", *8th Greek National Steel Structures Conference*, Tripoli, 2-4 Oct. 2014 (in Greek).
5. Vernardos, S.M. and Gantes, C.J., "Preliminary Feasibility Investigation of Sandwich-Type Shells for Wind Turbine Towers", *8th Greek National Steel Structures Conference*, Tripoli, 2-4 Oct. 2014 (in Greek).
6. Melissianos, V.E. and Gantes, C.J., "On the Efficiency of Flexible Joints in Mitigating the Consequences of Seismic Fault Activation on Buried Pipelines", *ARC'14 - Qatar Foundation Annual Research Conference*, Doha, Qatar, 18-19 Nov. 2014.
7. Melissianos, V.E. and Gantes, C.J., "Failure Mitigation of Buried Steel Pipeline under Strike-Slip Fault Offset Using Flexible Joints", *SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World*, Cambridge, U.K., 9-10 July 2015.

Book chapters:

1. Gantes, C.J., Bouckovalas, G.D., Melissianos, V.E. and Valsamis, A., "Pipeline – Fault Crossing: Structural Considerations on the Use of Flexible Joints for Mitigating a Potential Failure", *Jubilee Volume - Andreas Anagnostopoulos: 50 Years of Service at the National Technical University of Athens*, pp. 127-139, Athens, 2015.
2. Melissianos, V.E. and Gantes, C.J., "Numerical Modeling Aspects of Buried Pipeline – Fault Crossing", *Computational Methods in Earthquake Engineering - Vol. 3*, edited by M. Papadrakakis, V. Plevris and N.D. Lagaros, Computational Methods in Applied Sciences 44, Springer Verlag, 2017.
   doi: http://dx.doi.org/10.1007/978-3-319-47798-5_1

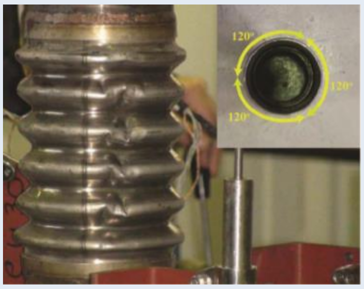
Description of ENNSTRAM's activities on buried pipelines

Buried pipelines transporting oil and natural gas are long cylindrical steel shells, commonly configured as continuous, with in-situ welding between adjacent parts. The use of flexible joints between steel segments in regions of anticipated large ground movements (e.g. active faults or landslides), has been investigated as an innovative protection measure. This enables the pipeline to sustain larger ground movements by localized deformation at the joints, while the steel parts remain essentially undeformed. Appropriate configuration and properties of flexible joints have been proposed, approximate analytical and more exact numerical analyses methodologies have been developed, and design guidelines have been formulated.

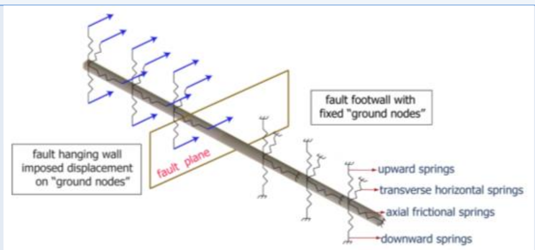
Experimental investigations of pipelines with flexible joints

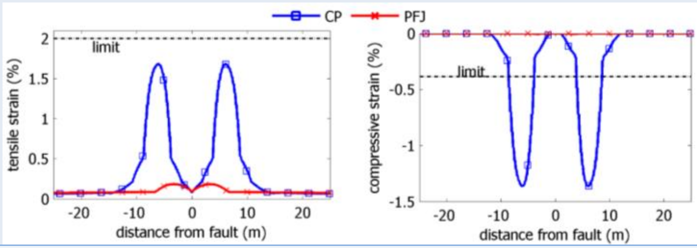
Specimens of continuous pipes and pipes with internal flexible joints under imposed transverse displacement, modeling seismic fault rupture, were experimentally investigated. Three-point bending tests were performed modeling the deformation of buried pipes subjected to fault offset. Tests were also conducted to estimate the properties of the flexible joints. Results confirmed very significant contribution of flexible joints in strain reduction, thus providing strong promise of effective protection of buried pipes from local buckling of pipe wall and tensile fracture of girth welds between adjacent pipeline segments. Experimental results have been sufficiently reproduced by numerical simulation accounting for geometric and material nonlinearities.



Numerical investigations of buried pipelines with flexible joints

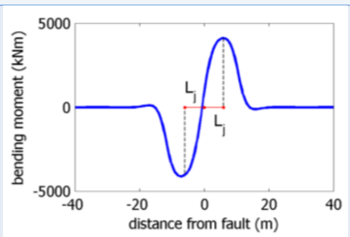
Advanced 3D nonlinear finite element modeling of buried pipes was implemented to investigate the effectiveness of flexible joints in terms of strain reduction. Extensive parametric numerical investigation of buried pipes with joints under strike-slip fault rupture was carried out on all parameters affecting the mechanical behavior, such as pipeline–fault crossing angle, fault offset magnitude, joint angular capacity, burial depth and diameter over thickness ratio. The effectiveness of joints has been compared to other protection measures that are commonly applied in engineering practice with very promising results.

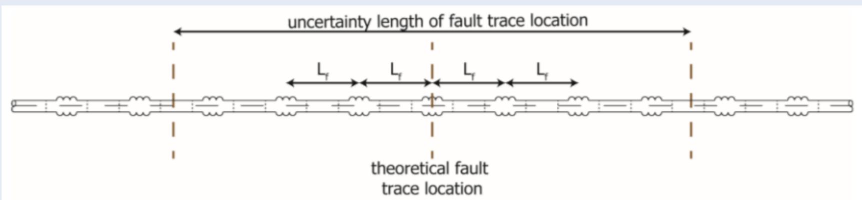




Preliminary design guidelines for buried pipelines with flexible joints

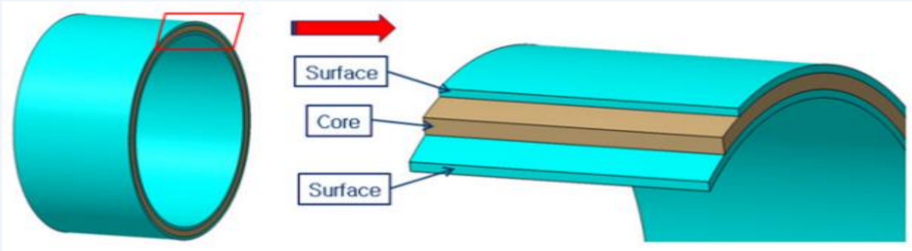
Results obtained from the parametric studies have highlighted the key factors affecting the behavior of pipes with joints under faulting. Preliminary design guidelines were formulated by considering these factors and taking into account the fault trace uncertainty. Design limits for every critical parameter were provided. In order to achieve a balance between joint effectiveness and economy, joints should be integrated at equal distance L_f along the entire pipeline length, where the fault trace might appear on the ground surface. Distance L_f is estimated based on the distance L_j that is obtained from the bending moment distribution of the continuous pipe, considering that hinged bellows are integrated near the location of the maximum expected bending moment.





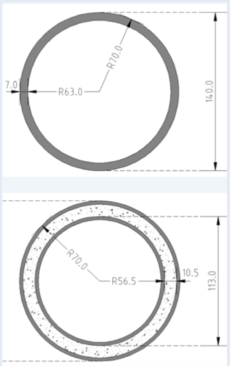
Description of ENNSTRAM's activities on wind turbine towers

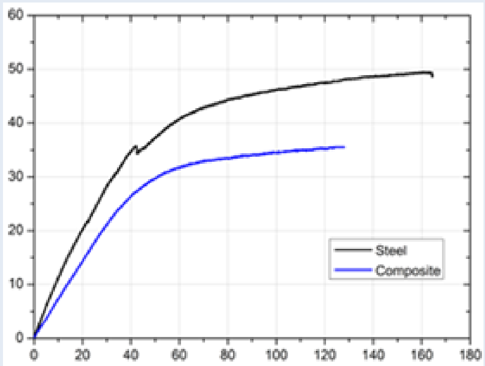
Better exploitation of wind potential requires taller wind turbine towers with larger diameter blades. For such towers the alternative solution proposed in this project is to replace the traditional conical steel shells by a sandwich-type shell, consisting of an inner and an outer steel plate (faces) with a lightweight fill material (core) in between, thus achieving high stiffness with small weight, as well as high damping. Suitable thickness of faces and core and fill material properties have been proposed and design guidelines have been formulated, incorporating optimization of geometry and materials.



Experimental investigations of sandwich-type wind turbine towers

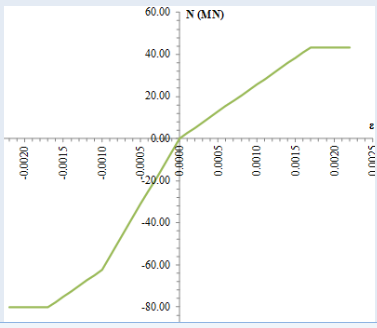
Cantilever cylindrical hollow specimens were constructed, having both solid steel section and sandwich section, and were subjected to bending in order to compare their structural behavior. The core of the sandwich section was filled with high strength, self-compacting mortar due to feasibility of unvibrated concreting of the narrow space between the faces. The experimental results confirmed the predicted behavior of the two specimens, proclaiming the sandwich concept as a more economical solution.

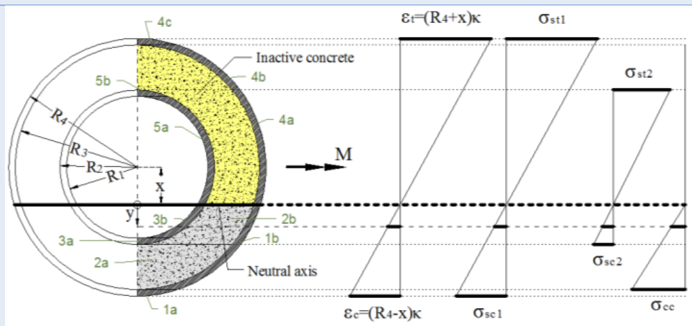




Analytical investigations of sandwich-type wind turbine towers

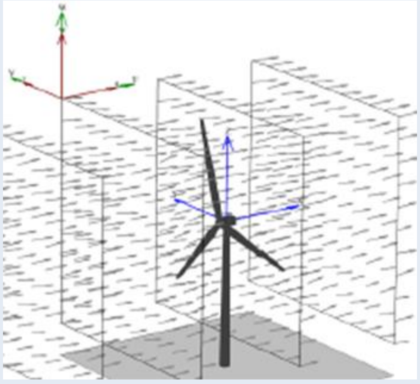
The sandwich section's behavior under axial loads is graphically presented below left. The response of the section under bending moment was approached by firstly dividing the section into several sectors, as shown below right, assuming the illustrated stress and strain distributions in the elastic range and corresponding ones in the elastoplastic range, enforcing force and moment equilibrium, performing the pertinent integrations per sector for a given curvature value, determining the neutral axis position through an iterative procedure, and then calculating the corresponding moment.

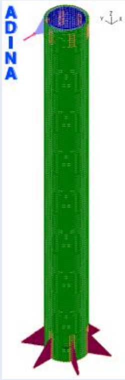


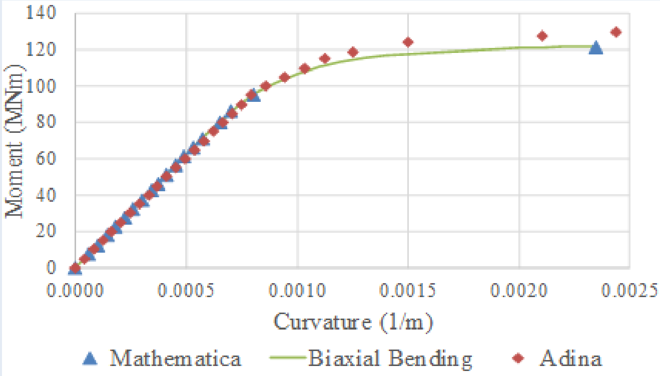


Numerical investigations of sandwich-type wind turbine towers

The aerodynamic response of the wind turbine tower was simulated using public domain software tools TurbSim, AeroDyn and FAST developed by the National Renewable Energy Laboratory (NREL) and the National Wind Technology Center (NTWC), which produce realistic artificial wind velocities and loading time histories. More refined finite element models in software Adina as well as simpler hybrid analytical-numerical models using Mathematica were developed and analyzed, demonstrating good conformance with analytical results.







Preliminary design guidelines for sandwich-type wind turbine towers

Extensive parametric analyses were performed in order to investigate the influence of different combinations of key-factors on the section's flexural stiffness and strength, assuming a sandwich section with an external diameter of 4 m, which is a common upper limit dictated by transportability constraints. Key-factors are the thicknesses of core and faces regarding the geometry of the section, and yield strength and Young's modulus of steel and concrete, as far as material properties are concerned. Typical results are presented below. The proposed solution is a hybrid one, consisting of sandwich-section segments near the tower's base and steel-only-section segments near the top of it, consequently achieving optimal manufacturing economy as well as structural behavior.