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Nonlinear modelling for Offshore Robustness. A sensitivity study.

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Summary

The assessment of existing offshore steel jacket structures for use beyond their initial life requires a proper design of an inspection plan aimed to constantly check-up the structural elements (both members and joints). There is consequently a need to define a set of indicators that, possibly combined with a continuous dynamic monitoring system, provides a reasonable measure of structural robustness and damage tolerance. To investigate these aspects the paper proposes to develop non-linear static pushover analyses to assess the system reserve strength: damages, or deteriorations, of primary and secondary structural components are assumed to evaluate their effects on the robustness of the structure and to evaluate the possibility to employ a structural monitoring system as a check-up of the integrity of the structural elements.

Keywords: Offshore steel jacket platform; Non-linear structural analysis, Static pushover analysis; Structural robustness; Inspection planning.

1. Introduction

Offshore steel jacket structures have been commonly used for oil (or gas) extraction in shallow and moderate water depth for decades, and a plethora of steel jacket platforms are still operational even if they reach the limits of their design service lives. Even if rather large reconstructions, repairs and inspections have to be executed, the use of existing installations beyond their design lives (due to, for instance, the extended oil reservoir estimates) is in various cases economically preferable. The assessment of such structures for use beyond their initial life requires a proper design of an inspection plan aimed to constantly check-up the structural elements (both members and joints). In principle, proper safety evaluation of an existing structure can be ensured by requiring compliance with the actual recommendations, even if how to perform such safety compliance with regards to life extension of existing structures is an open issue. Moreover, assessing additional fatigue life for a structure that has reached its original fatigue design life is not possible only using design regulations, even if no cracks have been detected. It is therefore of importance to develop a scheme which presents a minimum of work to be done in order to ensure proper future safety of a structure beyond its original design life. In this context the inspections, and the subsequent (if necessary) possible repairs, are so viewed as a safety barrier to prevent corrosion failure, fatigue failure, etc. in members and joints (and, of course, to repair them if they have occurred). The amount of inspections, their frequency and their typology (i.e. the proper selection of the elements and/or joints to check-up) is a critical issue (since, for instance, it may not be feasible to inspect all critical components), and inspection planning was for the last decade, and still is, based mainly on probabilistic analysis (Risk Based Inspection, RBI) [1] [2].

The paper aims to deepening these aspects analyzing the robustness of such structures in order to identify a set of indicators that provides a reasonable measure of structural robustness and damage tolerance. Consequently the paper aim to identify methods for evaluating the safety of a structure beyond its design life, taking into account that for a robust and damage tolerant structure the proper structural safety is not restricted by the occurrence of single (members and/or joints) component failures. In this context, robust and damage tolerant means that the structure has an acceptable probability of failure due to extreme loading in intact condition or with a single member or joint failure. The tasks that the paper approaches are then: a) Evaluate indicators for robustness and damage tolerance able to control if a wave overloading is acceptable in intact condition and with one member failed. The damage tolerance and robustness of the jacket structure is evaluated by means of pushover analyses, and indicators are evaluated; b) Evaluate the possibility to employ a dynamic monitoring as an effective instrument to check-up the presence of a single member or joint failure, and consequently as an instrument to prevent developing into multiple joint and member failures. To this aim a specific case study is analyzed and used as a reference: the Vega A Offshore platform, an eight-leg steel jacket platform operating in the Sicily Channel, 25 km offshore in 122.3 m water depth. The evaluation of the indicators of the system reserve strength is based on non-linear collapse analysis (static pushover analysis): damages, or deteriorations, of primary and secondary structural components are assumed in order to evaluate their effects on the robustness of the structure. The final aim of this study is to evaluate the possibility, through the evaluation of the robustness indicators, to combine a dynamic monitoring system with an inspection plan in order to optimize the amount of inspection.

2. The Vega A Offshore Platform

The fixed offshore steel platform analysed in the paper is the Vega A platform, an eight-leg steel jacket platform operating in the Sicily Channel 25 km offshore in 122.3 m water depth. The Vega A platform comprises a steel Jacket platform (Fig. 1), which is 140 m high, having eight columns connected using horizontal bracings with four vertical bracings in the transversal direction and two vertical bracings in longitudinal direction. The dimensions of the jacket at the sea bed are 70 m by 48 m, while at the top they are 50 m by 18 m [2] [4]. Six horizontal bracing frames, spaced at approximately 24 m, are also used to support the well conductor guides. The jacket is supported by 20 vertical steel piles, 85 m long with a diameter of 2.6 m. These piles have been driven to a depth of 65m below the seabed by means of an underwater ham-mer. Since March 1988 the platform structural behaviour has been object of study by the University of Florence and a system of vibration monitoring is still active on the platform, which records many types of structural data [5].

Assessment of an existing structure is performed in order to extend service life of the facility, as new methods of production and new discoveries may result in a request for life extension. The analysis is typically performed using a non-linear finite element program taking into account nonlinearities in both geometry and material behaviour.

Fig. 1: Vega A, Steel jacket platform.

3. The Non-linear pushover analyses

Non-linear collapse analyses are employed to evaluate the indicators of the system reserve strength: damages (or deteriorations) of structural primary and secondary components, members or joints, are assumed in order to evaluate their effects on the robustness of the structure. The non-linear analyses were developed in the framework of collapse analysis trough the pushover analysis technique using a non-linear finite element code (ANSYS [6]) and taking into account nonlinearities in both geometry and material behaviour. The non linear analyses were carried out on a 3D numerical model where main columns and vertical and horizontal bracing elements were modelled by means of beam elements with elasto-plastic behaviour. The final 3D model (Fig. 2) consists of 175 joints and 478 1D elements corresponding to 1002 degrees of freedom.

Load distributions derived by waves are modelled using the Stokes 3th order theory and, under conditions of constant gravity loads, the horizontal loads induced by waves were monotonically increased until collapse. The loading, in particular, is defined by a permanent load case (e.g. weight of topside and jacket, equipment weight on topside and buoyancy of the jacket) and by an environmental (wave and wind and current) load case. The permanent load case is first applied to the structure, and then the environmental load case is applied to the structure. The environmental load is stepped onto the structure until the structure collapses, and the collapse of the structure is defined by lack of ability to withstand the horizontal load. In this context the collapse load is defined as the maximum load the structure can withstand, before the load-deflection capacity curve starts a negative trend.

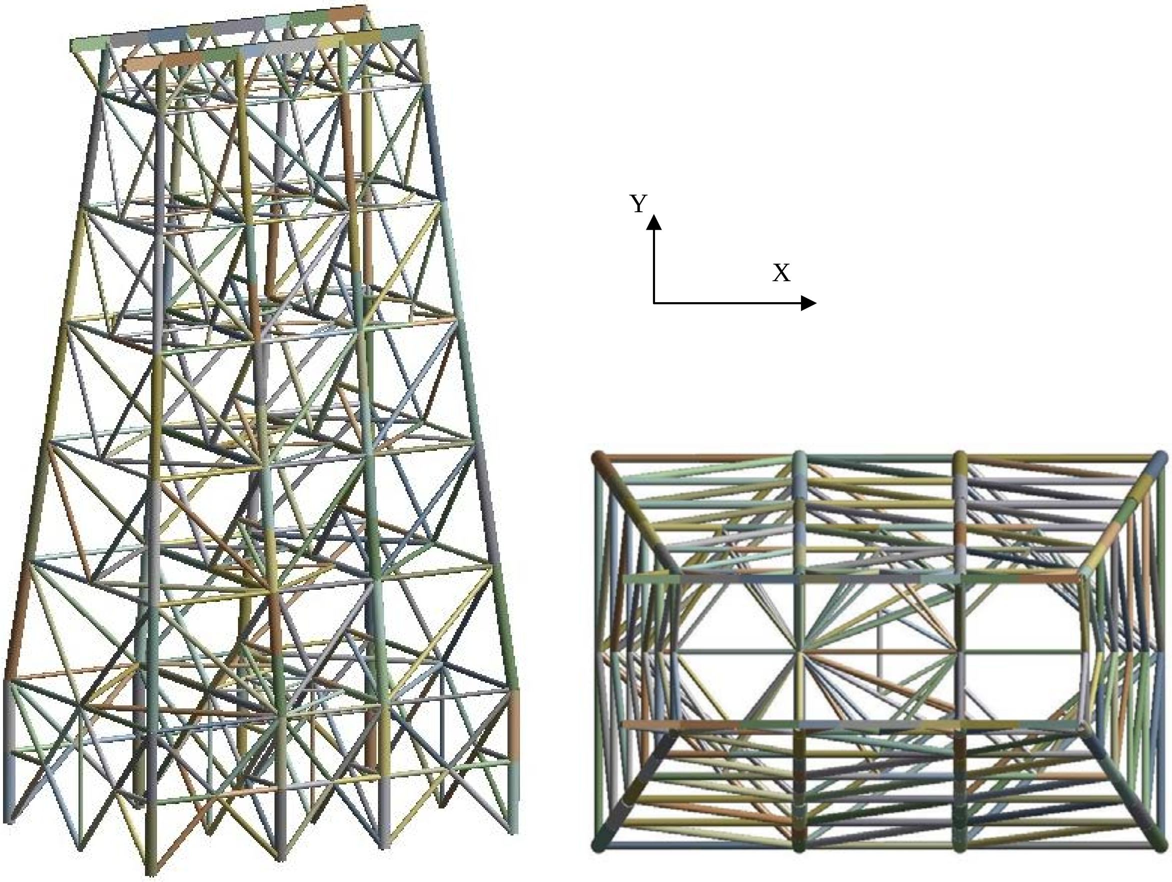
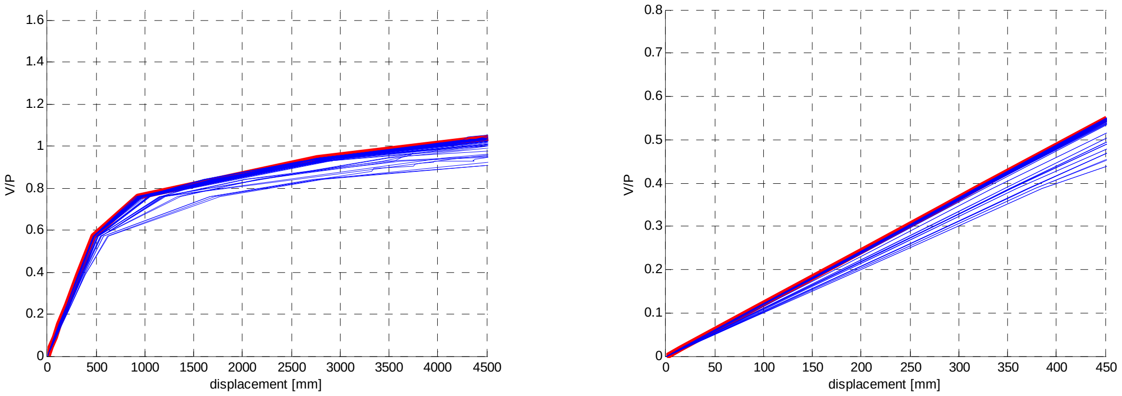
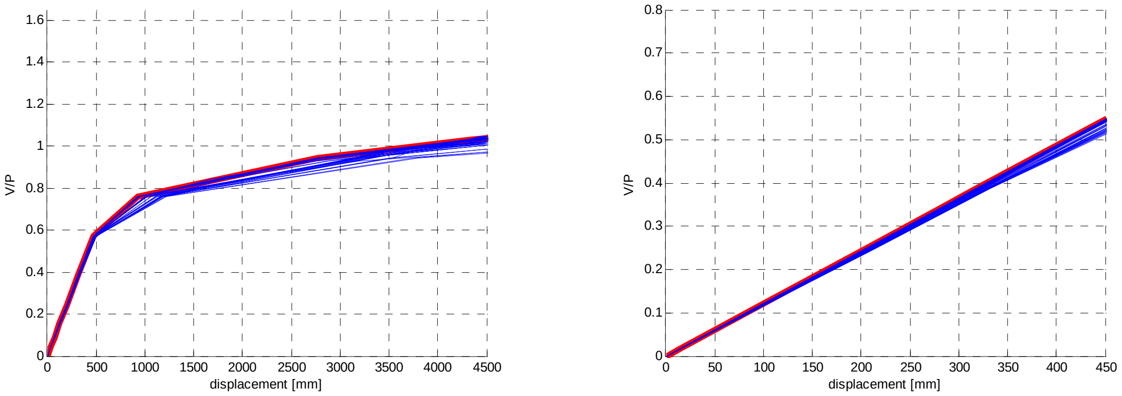


Fig. 2: Vega A, numerical model.

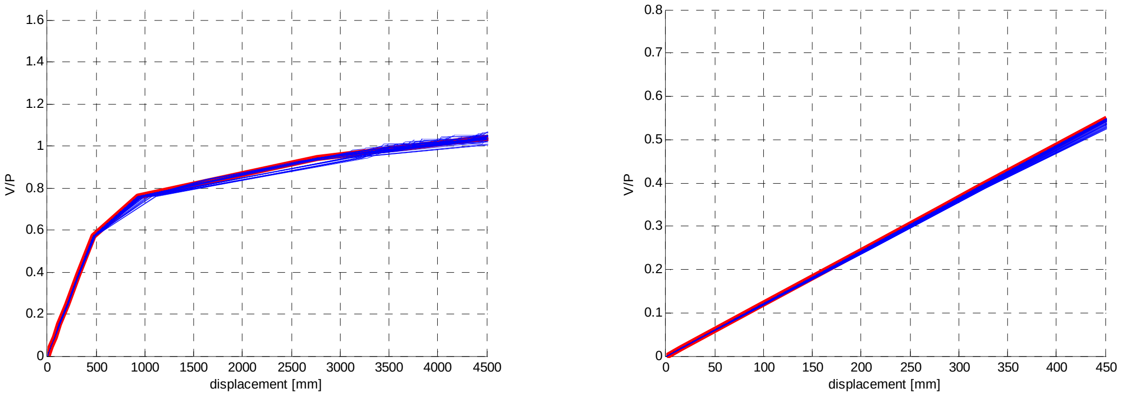
The analyses were developed assuming the environmental load distribution acting in the two main direction of the offshore platform (the X-direction, the longitudinal one, and the Y-direction, the transversal one, Fig. 2). In addition two further directions were considered: one with an angle of 30° with respect the longitudinal direction and one with an angle of 60° again with respect the longitudinal direction. For each load direction several damage scenarios were considered assuming the failure of a member or a joint. From a numerical point of view the failure of a member, or a joint, is assumed simply removing the corresponding beam element in the numerical model. To discuss the results the scenarios are grouped in three categories: a) the elements of the eight-leg (approximately 65 beam elements); b) the elements of the vertical bracing (approximately beam 175 elements); c) the elements of the horizontal bracing (approximately beam 190 elements). Each analysed damage scenario corresponds to the failure of one of these elements. The collapse analyses (pushover analyses) were thus performed to estimate the collapse capacity of the jackets assuming different damage scenarios and to evaluate how sensitive is the reserve strength ratio (RSR) of the Vega A jackets with respect to the damage scenarios. In this context the nonlinear redundancy analysis is regarded as a possible sound method to be combined with other indicators of safety, or with a dynamic monitoring, to ensure proper future safety of a structure beyond its original design life. Overall, about 1700 pushover analyses were performed.



(a) Damage of main leg (d) Damage of main leg, detail

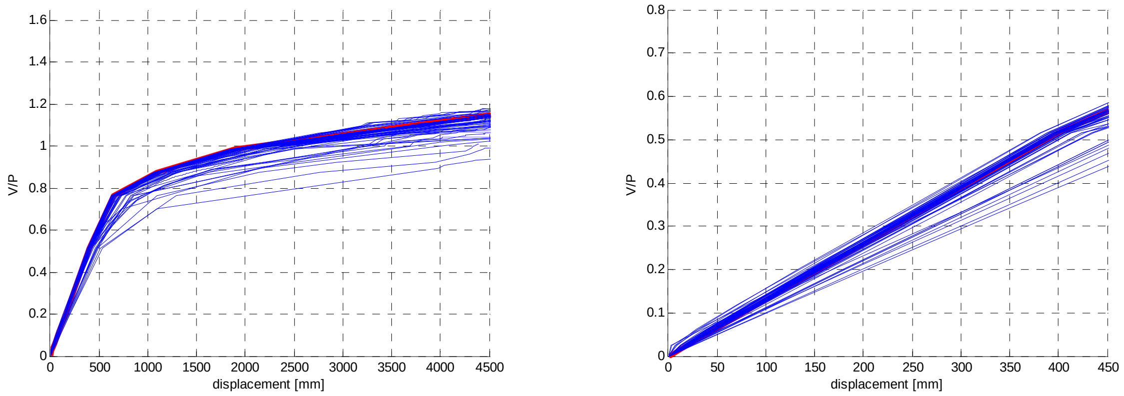


(b) Damage of vertical bracing (e) Damage of vertical bracing, detail



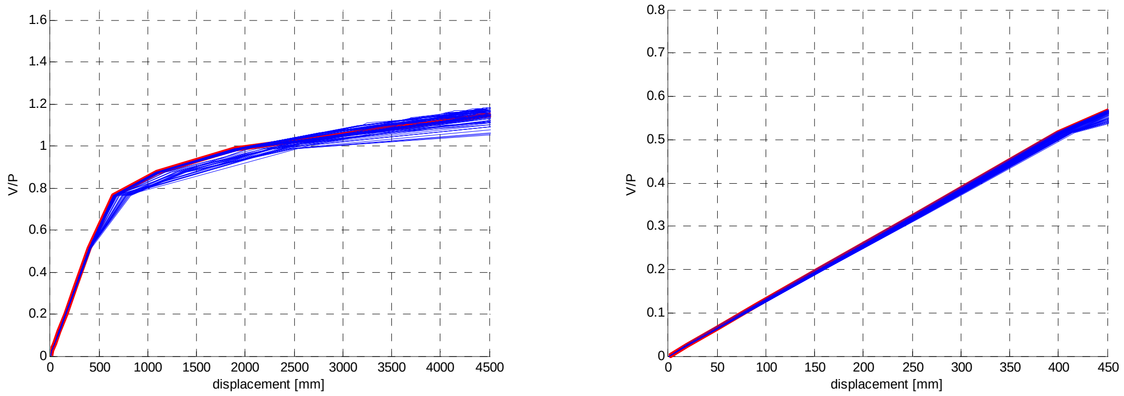
(c) Damage of horizontal bracing (f) Damage of horizontal bracing, detail

Fig. 3: Pushover analyses x-direction (0°): capacity curves.



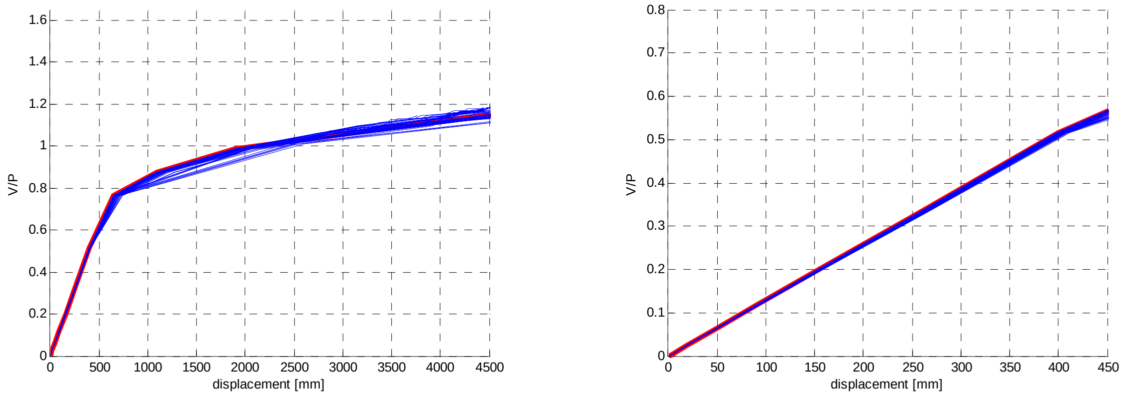
(a) Damage of main leg

(d) Damage of main leg, detail



(b) Damage of vertical bracing

(e) Damage of vertical bracing, detail

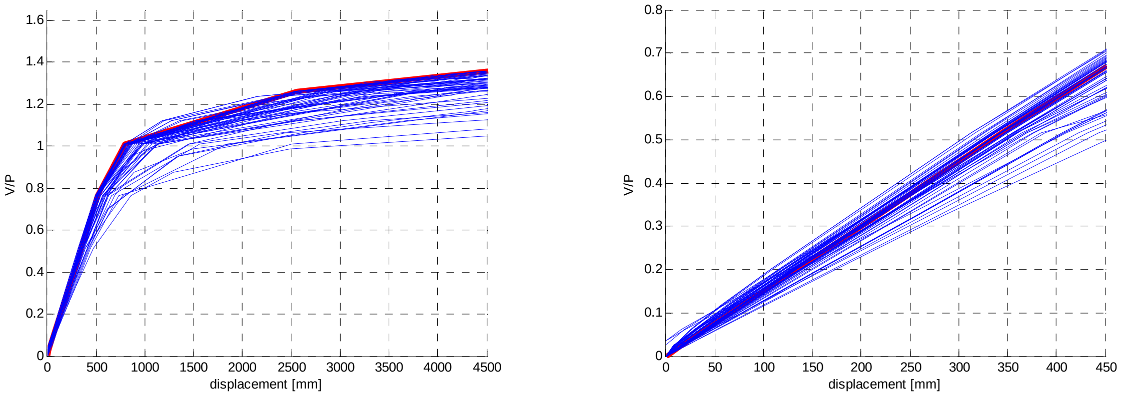


(c) Damage of horizontal bracing

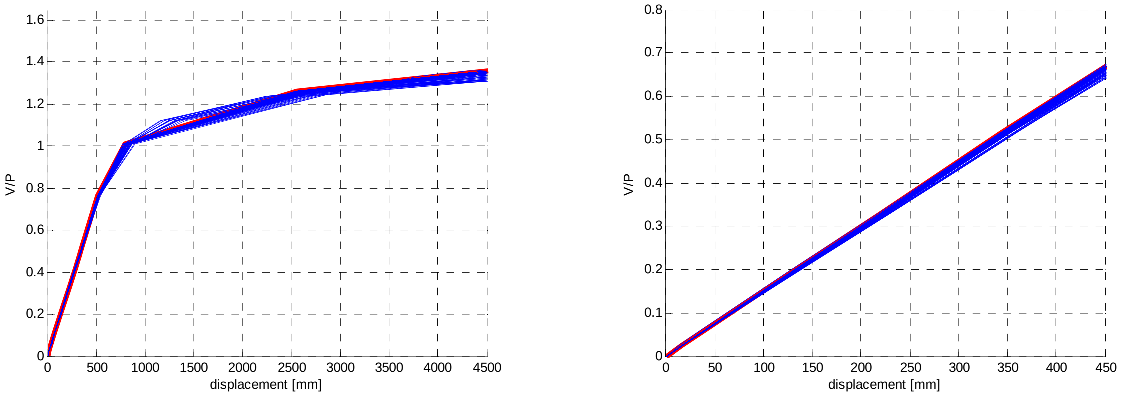
(f) Damage of horizontal bracing, detail

Fig. 4: Pushover analyses diagonal direction (30°): capacity curves.

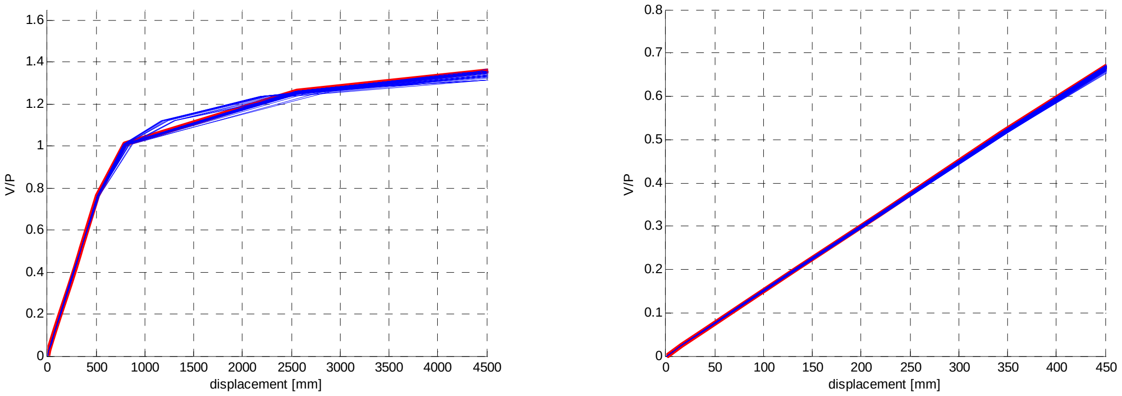
Results of the collapse analyses are reported in Fig. 3-Fig. 6, that show the capacity curves for each assumed direction horizontal loading direction (0°, 30°, 60° and 90°). As an example Fig. 3 reports the results in terms of pushover curve in case of loading along the longitudinal direction (x-direction). Fig. 3a compares the pushover curve of the undamaged structures (the marked line) with the corresponding ones obtained assuming a failure of a beam element in the leg of the platform. Fig. 3b compares the pushover curve of the undamaged structures with the corresponding ones obtained assuming a failure of a beam element in the vertical bracing of the platform. Fig. 3c compares the pushover curve of the undamaged structures with the ones obtained assuming a failure of a beam element in the horizontal bracing of the platform. Fig. 3d-e-f report a detail of the pushover curves in the first step of the analyses, showing the change in stiffness.



(a) Damage of main leg (d) Damage of main leg, detail



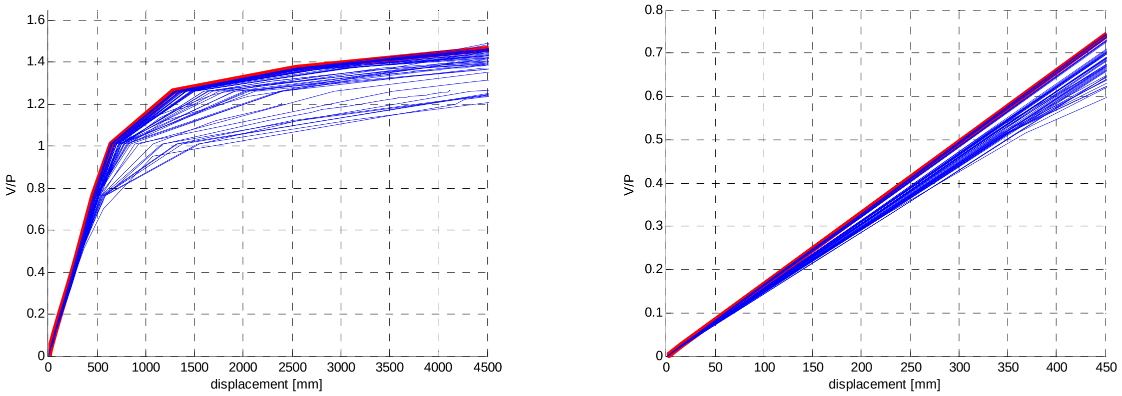
(b) Damage of vertical bracing (e) Damage of vertical bracing, detail



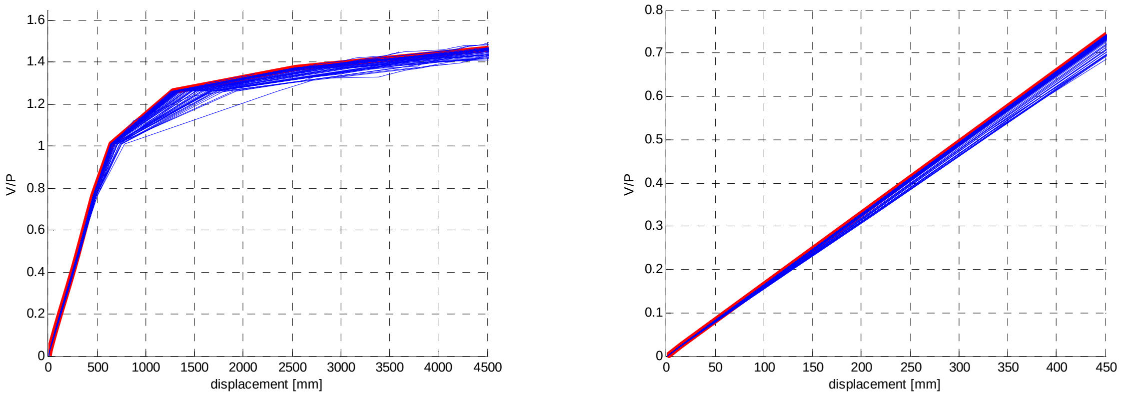
(c) Damage of horizontal bracing (f) Damage of horizontal bracing, detail

Fig. 5: Pushover analyses diagonal direction (60°): capacity curves.

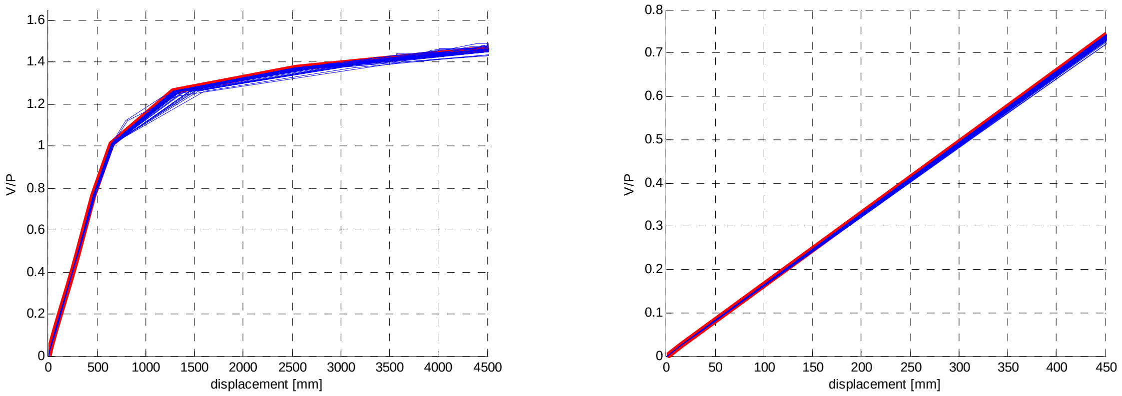
As a general comment it is possible to observe that for each considered loading direction a similar structural behaviour is obtained: the structure is more sensitive to failure of elements of the main leg with respect to failure of vertical or horizontal bracing. This is showed by both the change in the ultimate collapse load and the change in the initial stiffness of the structure. The results thus show that, taking into account that change in stiffness are reflected in change in main frequencies, a dynamic monitoring system able to evaluate the structural frequencies can be used as a sound indicator for main damage of the structure. Furthermore the results show that a (single) damage in horizontal or vertical bracing, thanks to the structural redundancy, does not affect the whole safety of the structure.



(a) Damage of main leg (d) Damage of main leg, detail



(b) Damage of vertical bracing (e) Damage of vertical bracing, detail



(c) Damage of horizontal bracing (f) Damage of horizontal bracing, detail

Fig. 6: Pushover analyses y-direction (90°): capacity curves.

This suggest that the structural system will normally fail as a result of a chain of failures of several components and that the system may fail due to several different failure modes corresponding to different chains of component failures. The failure modes of a structural system may be described by a fault tree and next step of the research will be devoted to the investigation of this fault tree.

4. Conclusive remarks

The paper, through the analysis of a specific case study, has deepened the aspects of robustness and damage tolerance of steel jacket platform as useful indicators for use of existing offshore installations beyond their initial design lives. In particular non-linear pushover analyses were performed analysing both the actual structural behaviour (without damage) and several damage scenarios (where a failure of members and/or joints is assumed). Comparisons between results are made, at this step, mainly analysing the capacity curves. The results show that the structure is mainly sensitive to damage in the main leg, and that the effects of the damage of one of these elements change significantly both the ultimate collapse load and the initial stiffness. Taking into account that change in stiffness are reflected in change in main frequencies, a dynamic monitoring system able to evaluate the structural frequencies can be used as a sound indicator for main damage of the structure. In addition the results show that a (single) damage in the horizontal or vertical bracing, thanks to the structural redundancy (damage tolerance), does not affect the whole safety of the structure (i.e. no appreciable change are visible in the ultimate collapse load). From a point of view this shows that structural redundancy is a key factor in design of such typology of structure. From another point of view the results shows a dynamic monitoring can be an effective instrument to check-up the presence of a single failure (and an instrument to prevent developing into multiple joint and member failures) and can be an effective component of an inspection planning. It should be observed that submarine inspections must be regarded mainly as a verification of the fabrication and the design analysis, if the design and fabrication has introduced errors of a significant factor, cracks would occur at an earlier stage of the life of the structure. Next step of the research will foresee a deeper analysis of the pushover results in terms of indexes such as the Reserve Strength Ratio (RSR), the damaged strength ratio (DSR) and the residual strength factor (RIF) in order to identify the set of safety indicators that provide a reasonable measure of structural safety against collapse and to offer hint about sequence of structural elements to be checked during submarine inspection. In addition an investigation of the failure modes of the structural system will be paid, to investigate a fault tree.

Acknowledgments

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References

[1] GOYET J., STRAUB D., FABER M. H., “Risk-Based Inspection Planning of Offshore Installations”, *Structural Engineering International*, Vol. 3, 2000, pp. 200-208.

[2] FABER M. H., “Reliability based assessment of existing structures”, *Progress in Structural Engineering and Materials*, Vol. 2, No 2, 2000, pp. 247-253.

[3] MUSSO A., SPADACCINI O., VIGNOLI A., “Structural dynamic monitoring on Vega platform: an example of Industry and University collaboration”, *SPE European Petroleum Conference*, 1996, Vol. II, pp. 623-632.

[4] BETTI M., SELLERI F., SPADACCINI O., “Non-linear structural analysis for in-situ platform demolition”, *Proceedings of the 9th International Conference on Structural Safety and Reliability*, 2005, pp. 1201-1207.

[5] GALANO L., SPADACCINI O., VIGNOLI, A., “Correlazione tra stato di danno e risposta dinamica di piattaforme fisse offshore”, *Atti del 4° Congresso AIOM*, 1996, pp. 301-308.

[6] ANSYS (Computer software), *Analysis reference manual*. Canonsburg, PA, SAS IP, Inc., 2007