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MEASUREMENT OF ACCELERATIONS AND KEEL LOADS ON CANTING KEEL RACE YACHTS

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SUMMARY

Canting keel boats can offer a significant increase in the performance of monohull yachts. Canting keel structures have generally been designed using a quasi-static analysis under a range of load cases. SP has developed load cases and analysis techniques for canting keel structures which have been used successfully for a range of yachts. As performance of the boats continually increases it is important to check that the load cases and assumptions used in the analysis remain appropriate.

SP has installed data acquisition equipment on two canting keel race boats, the Open 60 Hugo Boss and the 100 foot canting keel maxi yacht Wild Oats, during offshore races. The systems fitted to the boats included a number of accelerometers through the yacht and pressure sensors on the keel rams.

The data has been analysed to investigate the rigid body accelerations experienced by the boat and the loads generated in the keel structure. The results show that the boats experience significant rigid body accelerations, which in the case of the Open 60 approached the ultimate accelerations used in the analysis of the keel structure. However the loads in the keel structure were significantly lower than would be calculated using a quasi-static analysis with the measured accelerations. This discrepancy is due to the flexibility of the keel structure, which effectively results in the keel bulb seeing a lower acceleration than the rigid body acceleration that the boat would suggest.

The dynamic response of the keel structure to impulse loading is investigated, and the load cases and assumptions currently used are shown to be appropriate for these keel structural arrangements. Design of novel keel structures, especially those with keel fins which are significantly stiffer in transverse bending, may require analysis of the dynamic response of the keel structure at the design phase to ensure that the load cases are appropriate.

1. INTRODUCTION

Canting keels can be used on sailing yachts to significantly increase the stability of the boat with only a small increase in weight of the keel system. This is achieved by moving the keel bulb laterally by swinging the keel to windward.

Hereshoff is attributed with pioneering the concept of the canting keel in the early part of the 20^{th} Century, but the first use of a canting keel in a racing yacht was not for some time after this.

No doubt yachting historians (and some patent lawyers) can comment on who did the “first” canting keel, but canting keels were seen in Mini Transat boats in the early 1990’s with Michael Dejoyaux sailing the Mini Transat in 1991 in a boat that had been modified to include a canting keel.

Canting keels then quickly moved into the Open 60 class of offshore boats, and Isabelle Autissier sailed the 1993-94 BOC challenge in Ecureil Poitou-Charette II, a Berret designed yacht with a canting keel. Christophe Augain won the 1996-97 Vendee Globe in Geodis, which had been converted to a canting keel, and since then every solo round the world race has been won by a boat with a canting keel.

SP first became involved with engineering canting keel boats with the Fabio Buzzi Open 60’ “Juno Plano” in 1992. Since then we have been involved in the structural engineering of more than 20 canting keel yachts, from a 30 foot inshore racer to the 140 foot “Mari Cha IV”, which has a single keel ram that apparently is capable of lifting a jumbo jet.

During this time we have developed load cases and analysis techniques that we have used to design the composite structures supporting the keel systems. As performance of the boats continually increases, it is important to check that the load cases remain appropriate for these yachts.

2. CURRENT LOAD CASES

As for a fixed keel, the primary loads on the keel structure are due to [1]:

- Transverse righting moment
- Grounding (longitudinal loads from running aground)
- Pounding (vertical loads from running aground)
- Slamming (vertical loads due to waves acting on hull bottom)
- Pitching (rotation about transverse axis due to waves acting on hull bottom)
- Inertia (stopping suddenly in a wave)
- Combinations of the above

Current structural design criteria for canting keels are generally based on quasi-static analysis of the keel structure under a number of design load cases. These load cases tend to be derived by grouping the loads into a number of worst case scenarios.

Derivation of the worst case loads for canting keel boats is complicated by the fact that the bending moment in the keel fin can be influenced by the yacht heel and keel cant angle, and the assumed acceleration envelope of the yacht. In general both fixed and swing keel yachts experience higher accelerations in the vertical direction of the boats frame of reference, and this can be more marked for canting keel boats which tend to sail more upright and faster than conventional keel yachts.

A brief review of some design criteria are included below.

2.1 ABS GUIDE

The ABS guide for classing offshore racing yachts [2] [3] has generally been regarded as the industry standard for scantlings of sailing yachts. These guidelines do not explicitly cover canting keel boats, but they define three load cases for keel structures, a transverse load case, a longitudinal grounding load case and a vertical slamming load case.

2.2 VOLVO 70 CLASS RULES

The Volvo 70 class rules [4] include a requirement that the structure be fit for purpose and that the structural design should meet the requirements of a suitable structural guide or standard. In addition there are specific requirements for the keel and bulb assembly, canting mechanism, bearing arrangements and appendage compartment. These consist of three load cases, a transverse load case with the fin centred, and grounding and vertical slamming cases which must be considered with the keel at any cant angle.

2.3 IMOCA CLASS RULES

The International Monohull Open Class Association Open 60 class rules [5] simply require that 'The boat shall be constructed in such a way as to be able to withstand, without irreparable damage, the forces of nature which it is intended to have to face in the course of races classified by the ISAF OSR as category 0.' Category 0 races are defined by the ISAF OSR rules [6] as 'Trans-Oceanic races…where yachts must be…capable of withstanding heavy storms'.

2.4 SP KEEL LOAD CASES

SP consider a range of load cases to cover the primary loads described above. For canting keel boats we combine the vertical slamming and transverse righting moment accelerations to allow the interaction between the heel and cant angle to be considered [1].

For this ultimate load case a 3g transverse load, a 4.5g vertical load and a combined load case dependant on the yacht being considered are used to define an acceleration envelope. An example of the acceleration envelope for a 60 foot canting keel boat is shown in figure 1.

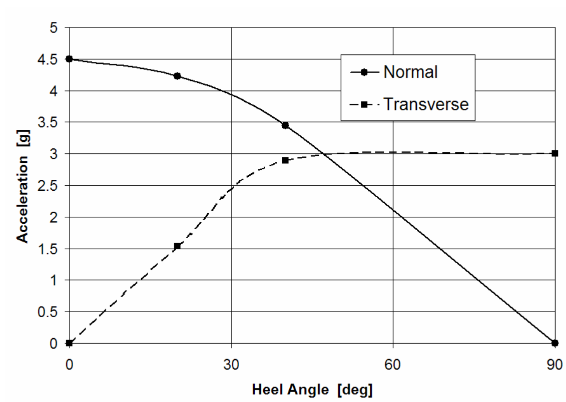

Figure 1 : Typical SP design acceleration envelope for a 60 foot canting keel boat. The "Normal" component always acts parallel to the yacht vertical axis, and the "Transverse" parallel to the boat transverse axis.

This acceleration envelope is used to calculate the keel reaction loads over a range of heel and cant angles. An example of the lateral loads seen by the forward keel pivot on a 60 foot canting keel yacht is given in figure 2. In this case the peak loads are seen at maximum cant when heeled at around 40 degrees.

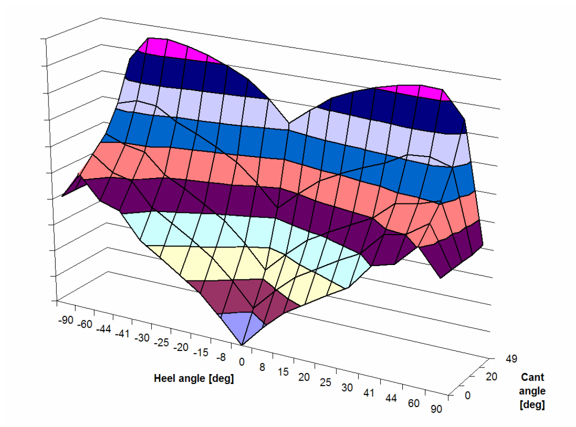

Figure 2 : Calculated forward keel pin lateral loads on a 60 foot canting keel boat using SP sailing load cases

2.5 COMPARISON OF KEEL STRUCTURE TRANSVERSE LOAD CASES

The ABS guide and Volvo rule both define a 1g transverse load case. ABS requires a safety factor of 2 for yield strength and 2.86 for the ultimate strength of the keel structure, but does not define a specific safety factor for the composite supporting structure under this load case. The Volvo rule requires a safety factor of 3 for the ultimate strength of the composite structure. This gives an ultimate transverse load case for the composite structure of 3.0g. The vertical load case for the Volvo rule would apply an ultimate acceleration with a transverse component of 2.9g when at maximum cant.

A typical SP canting keel load case for an Open 60, which considers the range of cant and heel angles, would result in a maximum ultimate transverse acceleration of just under 4.5g.

3. LOAD MEASUREMENT

3.1 SP DATA AQUISITION KIT

SP has a number of data acquisition systems. These are based on systems that were originally specified by one of the authors for measuring accelerations on Open 60 yachts competing in the Vendee Globe in 2004 [7]. The systems consist of an autonomous data logger, which can be connected to a range of sensors and also logs data from the yacht instruments to provide position and environmental information.

A typical set up is illustrated in figure 3. A number of accelerometers are located around the boat which enables the motions of the boat to be derived. Additional sensors can be added to measure loads on various parts of the yacht.

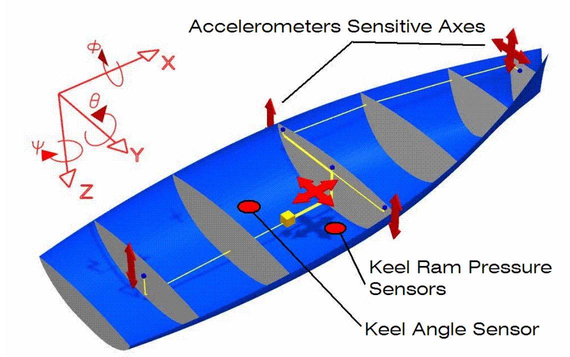

Figure 3 : Typical layout of data acquisition sensors

Figure 4 : Data logger

3.2 DATA ACQUISITION FOR KEEL LOADS

We were fortunate recently to be able to fit data acquisition kit to two canting keel yachts competing in offshore races. The first yacht was the Open 60 “Hugo Boss”, a Marc Lombard design. The second yacht was the Reichel Pugh designed 100 foot canting keel maxi “Wild Oats”.

The systems fitted to the boats included the accelerometers mentioned above and pressure sensors on the keel hydraulic rams. These allowed the loads on the ram bearings to be calculated.

The data acquisition kit was fitted to Hugo Boss for the 2006 Velux 5 Oceans Race and to Wild Oats for the 2006 Sydney – Hobart race.

3.3 RESULTS

Rigid body motions of the yachts have been calculated from the measured accelerations. Figures 5 and 6 show how frequently various magnitudes of accelerations transverse to the keel fin were encountered at the keel centre of gravity.

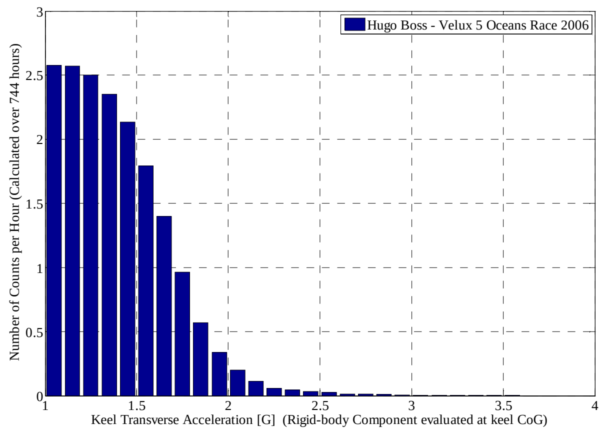

Figure 5 : Histogram of rigid body keel accelerations on Hugo Boss. The number of counts corresponds to the average number of instances per hour when the keel acceleration exceeds the given value.

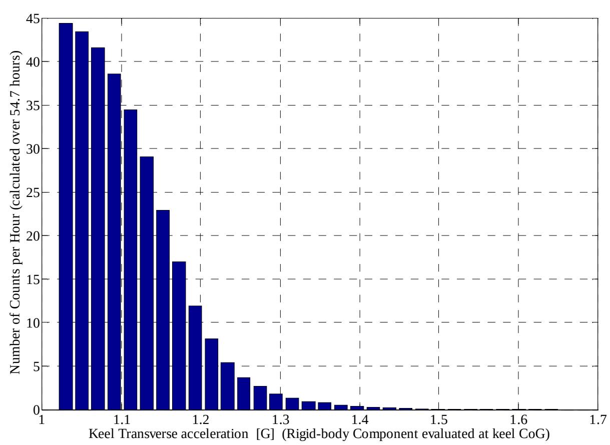

Figure 6 : Histogram of rigid body keel bulb accelerations on Wild Oats. The number of counts corresponds to the average number of instances per hour when the keel acceleration exceeds the given value.

These accelerations are the rigid body motions that the boat would like to apply to the keel bulb, and these would normally be used to calculate the inertial loads on the keel structure. It can be seen that the derived rigid body motion accelerations for the Open 60 approach the ultimate load cases typically used for the design of keel structures. The peak accelerations on the maxi yacht seen during the logging period are significantly lower than those seen on the Open 60. This is due partly to the hull shapes of the boats and also to the significant difference in displacements as one boat is around 2.5 times the displacement of the other.

The vertical acceleration and keel ram load time history for a typical slam on Hugo Boss and Wild Oats are shown in figures 7 through 10.

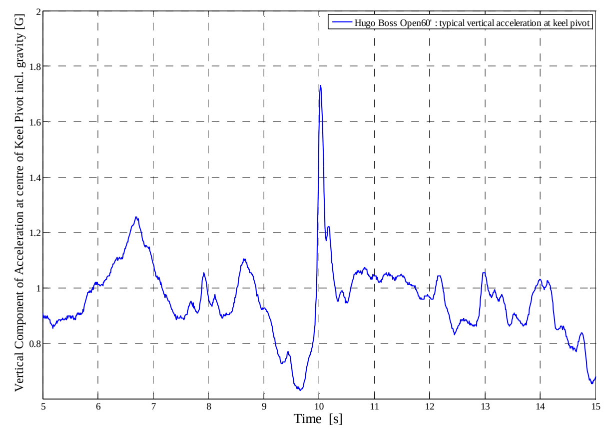

Figure 7 : Vertical acceleration time history for a typical slam on Hugo Boss

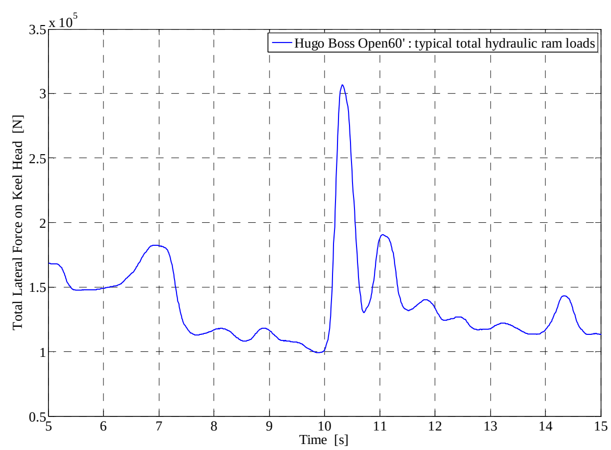

Figure 8 : Keel ram load time history for a typical slam on Hugo Boss

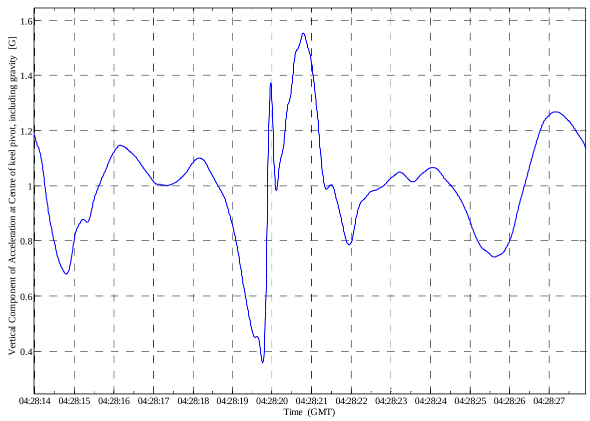

Figure 9 : Vertical acceleration time history for a typical slam on Wild Oats

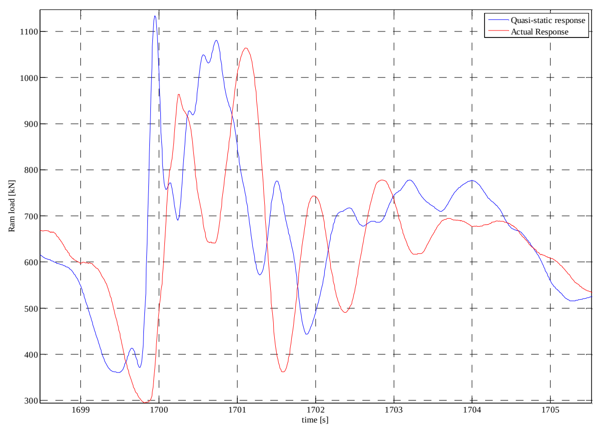

Figure 10 : Keel ram load time history for a typical slam on Wild Oats. The measured response (red line) is compared here with the load calculated using quasi-static assumptions (blue line).

The loads from the rams are significantly lower than would be calculated using a quasi-static analysis of the keel structure under the derived rigid body accelerations. This is due to the dynamic response of the keel structure to the impulse loading, which results in the keel bulb effectively seeing a lower acceleration due to the flexibility of the keel structure.

4. RESPONSE OF THE KEEL STRUCTURE TO IMPULSE LOADING

4.1 RESPONSE OF SYSTEMS TO IMPUSE LOADING

The behaviour of the keel under impulse loading can be understood by considering the response of a single degree of freedom system to impulse loads.

The response of such a system to an impulse is mainly dependent on the shape of the impulse and the ratio between the duration of the impulse and the natural period of the system [8], and can be summarised by the dynamic response shock spectrum. The peak magnitude of the response of the system to an impulse is normalised by the response of the system to a static load of the same magnitude. This ratio is then plotted against the impulse duration normalised by the natural period of the system.

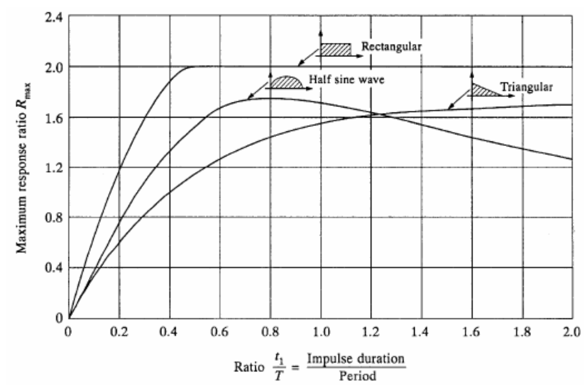

Figure 11 : Dynamic response spectra of a single-degree-of-freedom system to impulse load [8]

The keel structure is subject to inertial loads along with steady and unsteady hydrodynamic loads and there can be coupling between the transverse, longitudinal and torsional vibration modes of the structure. However, previous studies [7] have shown that the response of a typical keel system is in line with that of a single degree of freedom system, and the hydrodynamic forces tend to dampen the magnitude of the response of the keel structure. Figure 12 illustrates the effect of hydrodynamic damping on the response of a model Open 60 keel structure.

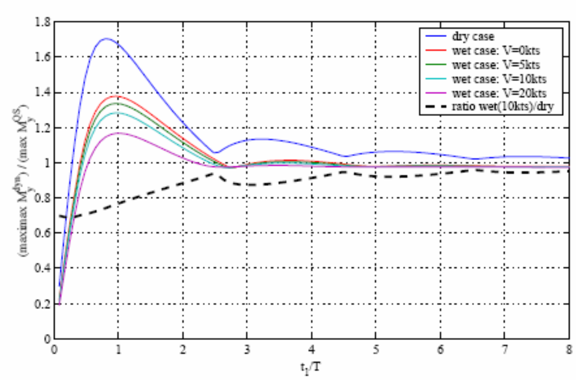

Figure 12 : Open 60 theoretical shock spectra: bending moment at keel root for half sine shaped transverse acceleration impulse [7]

4.1 CALCULATED RESPONSE OF KEEL STRUCTURE

The first measured natural frequency in transverse bending of the Wild Oats keel structure was 1.13Hz. Durations of the peak transverse impulse loads measured on Wild Oats were between 0.15 and 0.2 seconds. From this it can be seen that the ratio of impulse duration to natural period of the structure is 0.17 and 0.23. From analogy with a single degree of freedom system this would suggest a ratio of dynamic response to static response of 0.7 to 0.9.

Previous work has indicated that the natural frequency of Open 60 keel structures is in the region of 1.6 Hz [7]. This was calculated by measurement of the response of a fixed keel boat. The natural frequency of a canting keel system can be assumed to be similar to this as the mass of the keel and stiffness of the supporting structure are comparable. Duration of the peak impulse loads measured on Hugo Boss was typically 0.1 seconds. This gives a ratio of impulse duration to natural period of the structure of 0.16, and a ratio of dynamic response to static response of approximately 0.5.

Analysis of the measured keel ram loads compared to a quasi static calculation using the measured accelerations on the Open 60 show a ratio of 0.5. This indicates that the response of the keel structure to the impulse loads can be suitably modelled by a single degree of freedom system for these loads.

4.2 IMPLICATIONS FOR DESIGN LOADCASES

The accelerations seen on Hugo Boss were approaching the ultimate accelerations assumed in the quasi static analysis of the keel. However the dynamic response of the system resulted in the loads on the keel structure having an acceptable factor of safety.

Whilst this gives confidence that the design load cases and analysis methods are giving suitable safety margins for the current keel structures, it is important to understand what drives the dynamic response, so that we can be more confident that the load cases will be acceptable for new designs.

The canting keel structures investigated so far have a natural period which is significantly larger than the duration of the high acceleration impulses. This means that the response is driven by this ratio rather than the shape of the impulse, as we are in the left hand region of the graphs shown in figures 11 and 12.

If the ratio between the duration of the peak impulses and the natural period of the keel system increased, then this could result in significantly higher loads being seen by the composite support structure.

A finite element model of a typical 100 foot canting keel boat fin and bulb was built to determine the relative effect of the fin and composite stiffness on the natural frequencies of the structure. The composite structure is represented by a grounded spring. Initial stiffness of the spring was calculated from a finite element model of the composite structure.

Figure 13 : Idealised finite element model of keel structure

The finite element model was run with the composite stiffness and fin stiffness varied by ±20%. Results are shown in figure 14.

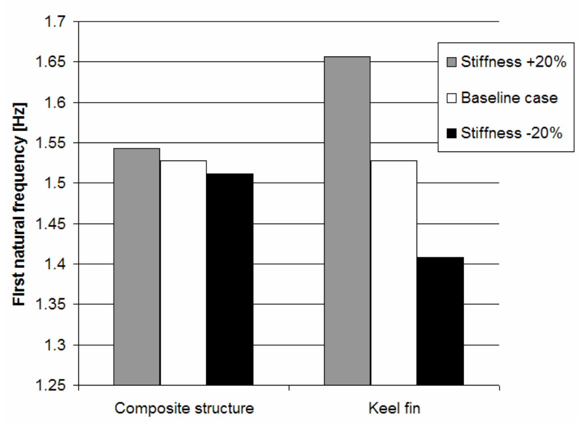

Figure 14 : Effect of composite structure and fin stiffness on keel structure natural frequency.

It can be seen that the stiffness of the composite structure only has a small effect on the natural frequency, but the fin stiffness can have a more significant effect.

5. CONCLUSIONS

Keel structures are generally designed using quasi-static analysis of inertial loads.

Accelerations and keel loads have been measured on two canting keel race boats during offshore races.

The peak impulse accelerations measured on the Open 60 were comparable to the ultimate load cases used for the keel structure design. Although the maxi yacht also encountered some severe weather the accelerations experienced by the boat were generally much lower.

The dynamic response of the keel structures to the impulse loads seen during the study is driven by the ratio of the duration of the impulse to the natural period of keel structure. For the structures considered here the dynamic response is significantly lower than the static response to an acceleration of the same magnitude.

The dynamic response of the system is important in determining the loads experienced by the keel structure. The current keel load cases and analysis methods used by SP give acceptable margins of safety for the keel structure configurations considered here.

If novel keel structures, especially structures with significantly higher transverse stiffness, are to be engineered, then it may be necessary to consider the dynamic response in more detail during the design phase to confirm that the keel load cases and analysis methods used give an acceptable safety margin.

6. ACKNOWLEDGEMENTS

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8. AUTHORS' BIOGRAPHIES

Mark Hobbs holds the current position of Senior Engineer at SP. He looks after a team of structural engineers specialising in conceptual design and analysis of composite structures, and manages to find time to keep his spreadsheets active working on projects varying from architectural sculptures and underwater power generation to Americas Cup yachts.

Paolo Manganelli holds the current position of Design Engineer at SP. He is actively involved in conceptual design and analysis of composite, working on a range of projects from Transpac 52's and Open 60's to 100 foot performance cruisers, and has achieved 'workplace guru' status in data acquisition and dynamic response of structures