7th International Conference on HYDROELASTICITY IN MARINE TECHNOLOGY
Split, Croatia, September 16th – 19th 2015

Rapid Prototyping of Flexible Models – A New Method for Model Testing?

S. S. Bennett,[1,*] J. Downes[1], T. Dickson[1], A. B. Phillips[2] and S. R. Turnock[1]

[1] Fluid-Structure Interactions Group, University of Southampton, UK
[2] National Marine Facilities, National Oceanography Centre, Southampton, UK

Abstract. To date hydroelastic towing tank models are generally segmented, flexible backbone or hinged models which provide an extremely limited representation of the ship structure and record loads only at a finite number of locations between segments. Fully flexible "hydro-structural" models, whilst providing a more accurate structural representation are rarely used due to expense and the complicated nature of their construction. Rapid prototyping is a powerful tool the potential of which is yet to be exploited in the marine industry. By using it to manufacture a realistic ship structure from materials of different properties, new model manufacturing paradigms may be explored. The focus of this paper is the initial findings from an investigation of the use of three-dimensional (3D) printing technologies for manufacturing structurally accurate flexible towing tank models. A detailed assessment is carried out of the material properties of 3D printed materials and their ability to model the scaled structural behaviour of a ship. Scaling implications when considering the realistic ship structure are presented and practical considerations for the construction of 3D printed towing tank models are discussed.

Keywords*: Model testing; manufacturing technologies; flexible models; structural model; rapid prototyping; fatigue; hydroelastic response.*

1. Introduction

The importance of assessing the consequences of wave-ship interactions from a structural assessment and ship structural design perspective is well established. Global and local loads, in particular when slamming occurs, should be assessed using advanced methodologies such as hydroelasticity that account for the inherent coupling between the hydrodynamic effects acting on the ship and the distortions due to the response of the hull girder. The use of model scale testing to predict the full scale hydrodynamic performance using rigid models is well established. In order to experimentally model the hydroelastic response, a flexible model is required.

[*] Correspondence to: S.S.Bennett@soton.ac.uk

Denchfield [1] discussed that to date flexible models can be either wholly elastic in nature or consist of a series of rigid segments connected via a flexible hinge arrangement or a flexible backbone such as shown in Figure 1.

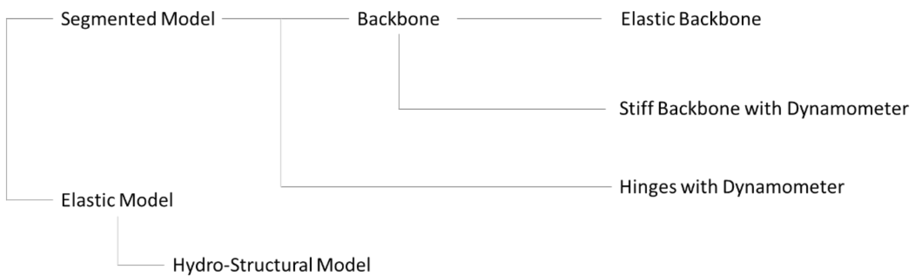

Figure 1 Flexible model construction methods.

A number of authors have used segmented models (either flexible backbone or hinged) for investigating the hydroelastic behaviour of ships. Bennett [2] presented the experimental results for vertical bending moments of a flexible backbone model of a naval frigate travelling at service speed in a range of head seas and long crested irregular waves. Drummen et al [3] use a flexible hinged model of a containership to measure vertical bending moments in steep regular and random waves. In Dessi and Mariani [4] a backbone model with a non-uniform cross section is applied to the investigation of the slamming induced loads of a high speed mono-hull. Lavroff et al [5] investigate the response of catamaran hullforms with a hinged model. Maron and Kapsenberg [7] reported on the design of a large containership model for testing in waves. In all these cases, careful consideration is given to properly scaling the global bending stiffness of the hull girder.

In order to suitably represent the torsional response, the aluminium or steel backbone commonly has cut outs included to achieve the appropriate stiffness (e.g. Kim et al. [8,9]; Zhu et al. [10]). This results in compromises in the responses that can be measured, also driven by factors including the model size and the ability to position a beam of suitable size within the model [7]. It should be noted that the use of plastics within the model may induce problems with the strain gauges as generated heat is not able to be suitably dissipated and therefore optical gauges should be used instead [7].

In general fully elastic models are rare due to cost and complexity of construction. One example is the S175 containership developed by Watanabe et al [11] from PU foam and resin model. Austin [12] reported on the design and construction of a rigid vinyl hydrofoil plainview (AGEH-1), including issues with global and local structural scaling. This model was used for structural testing only and not for hydrodynamic or hydroelastic analysis. Hay et al [13] developed a PVC model of a frigate with primary structural members represented.

If a hydro-structural model is suitably scaled, then there is the potential to provide more detailed understanding of the structural responses for the validation of numerical models such as hydroelastic finite element based analyses than segmented models. Recent advances in additive manufacturing (AM) technologies may support the manufacture of hydro-structural models. Small scale complex structures, which were previously prohibitively expensive or even impossible to produce, can now be manufactured at an acceptable cost. However in addition to ensuring that the model is representative of the geometric shape and able to represent the structural response in a suitable manner, the International Towing Tank conference (ITTC) [14] requires that the manufacturing of ship tank models be dimensionally accurate to within ±1.0mm of the intended scale length and breadth and a surface finish equivalent to that achieved by 400 grit wet and dry paper. The use of additive manufacturing technologies will need to be able to meet these requirements.

This paper presents an investigation of the potential for the use of the rapidly evolving 3D printing methodologies currently available for the construction of a hydro-structural model. The aim of this research is to establish the benefits and limitations of rapid prototyping technologies in the manufacture of ship models.

2. 3D Printing Methods

Fused Deposition Modelling (FDM) using acrylonitrile butadiene styrene (ABS) is one of the most common rapid prototyping technologies available [15]. Complex geometries can be produced by the layering of extruded material. ABS is a carbon chain polymer belonging to styrene terpolymer chemical family [16]. A fused deposition printer takes raw material in the form of a filament which is partially melted in a heated nozzle and deposited in small beads onto the build platform. Once an entire layer has been extruded, the build platform moves downwards in a distance equal to the layer thickness and the nozzle begins to deposit a new layer. The extruded material solidifies, cools and bonds with adjoining material. If there is any overhanging geometry which requires support in the build process, this is built in small columns which can be removed post-construction [17].

An alternative additive manufacturing method is Stereolithography (SL) which is a laser-based process that works with photopolymer resins to produce very accurate parts with a high quality surface finish. Supporting structures are required for overhanging geometry and the end product requires post-printing curing to fully harden the geometry. Selective Laser Sintering (SLS) uses a high power laser to fuse small particles of powdered material (metal, glass, plastic or ceramic) into three-dimensional shape. Unlike other additive manufacturing processes, SLS does not require support structures due to the fact that the part being constructed is surrounded by un-sintered powder at all times, allowing for the construction of previously impossible geometries. The process can be applied to metallic, plastic, ceramic, and glass materials.

An issue that affects all types of 3D manufacturing processes is the size of the components that can be constructed. Typical bed sizes for component printing are in the order of 635mm x 635 mm x 530mm, with the rare and very largest currently available being 4000mm x 2000mm x 1000mm.

For this project, FDM with ABS was used. When scaling the global and local structural properties of a ship are the material properties of the printed ABS are of importance. The FDM process means that these are not solely controlled by the properties of the extruded material, but are also impacted by the manufacturing process which is directionally dependent due to the nozzle forming the molten material, and has anisotropic qualities associated with inherent layering within the material. Ideally being able to control the material properties to be isotropic would ensure that the structural responses of the model were being more accurately modelled and not subject to directionality within the material. There is the potential for issues with the joining between layers and therefore the resulting strength of the manufactured component. Further issues include the potential for porosity in the material due to this layering process which could result in a non-watertight structure and the bed size of the printer being used; this influences the size of “block” which can be manufactured hence the need to join component blocks together to create a complete model. The key parameters affecting the properties of an FDM printed part are shown in Figure 2.

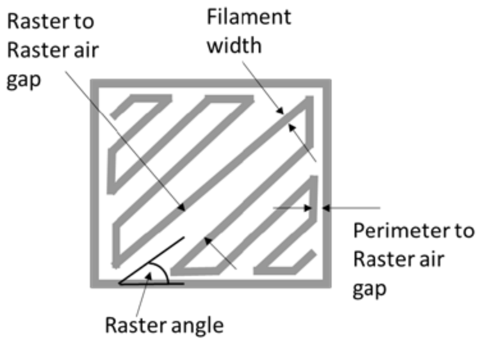

Figure 2 Key Parameters of FDM manufacturing process

3. Model Scaling

3.1. Global Scaling

Conventional segmented flexible models are designed to represent global bending responses. The non-dimensional equations which govern the bending of a transversely symmetric beam are given by:

$$V(x,t) = kAG(x)[\gamma(x,t) + \alpha(x)\dot{\gamma}(x,t)] \quad (1)$$
$$M(x,t) = EI(x)\left[\acute{\theta}(x,t) + \beta(x)\dot{\theta}(x,t)\right] \quad (2)$$

where *EI* is the Flexural rigidity, *kAG* the Shear rigidity, $\gamma(x,t)$ the Shear strain, $\alpha(x)$ the shear damping, $\theta(x,y)$ the Slope attributable to bending and $\beta(x)$ the bending damping.

These equations form the basis for the behaviour of a ship model response to wave excitation. To scale between model (subscript *m*)and full scale (subscript *s*) scaling laws need to be applied to the length scales (λ), time scales (*t*), flexural rigidity, and shear rigidity for the global behaviour [18]:

$$\lambda = \frac{L_s}{L_m} \quad (3)$$
$$t_m = \frac{t_S}{\lambda^{1/2}} \quad (4)$$

$$(EI)_m = \frac{(EI)_s}{\lambda^5} \tag{5}$$

$$(kAG)_m = \frac{(kAG)_s}{\lambda^3}. \tag{6}$$

3.2. Local Scaling

To develop a flexible model with representative local structure the behaviour of both plates and stiffeners needs to be considered. For the local behaviour of plates, then the following scaling should also be applied. This scaling is based on the behaviour of a clamped plate as shown in Figure 3.

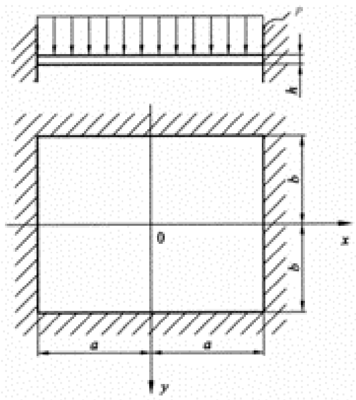

Figure 3 Clamped plate under lateral loading

If the displacement of the plate is given by:

$$\delta \propto \frac{Pb^4}{D} \tag{7}$$

where *P* is the lateral pressure and *b* the plate breadth. The flexural rigidity is given by

$$D = \frac{Et^3}{12(1-\nu^2)} \tag{8}$$

thus

$$\delta \propto \frac{Pb^4(1-\nu^2)}{Et^3} \tag{9}$$

where *v* is the Poisson's ratio, *t* the plate thickness and *E* the Young's Modulus.

Given that hydrodynamic pressure $P \propto \rho U^2$ is the primary driver for local structural response and the geometric similarity requirement gives $\delta_m \lambda = \delta_s$, then

$$\frac{P_m {b_m}^4 (1-{v_m}^2)}{E_m {t_m}^3} \lambda = \frac{P_s {b_s}^4 (1-{v_s}^2)}{E_s {t_s}^3} \tag{10}$$

Assuming that $\rho_s \approx \rho_m$ and recalling that $V_m^2 \lambda \approx V_S^2$ then the local plate characteristics can be found as

$$\frac{\mathrm{E}_m t_m^3}{(1-v_m^2)} = \frac{E_s t_s^3}{\lambda^4 (1-v_s^2)}. \tag{11}$$

The impact of scaling for both global and local effects needs to be considered carefully. The influence of Poisson's ratio need to be accounted for when considering the materials commonly used for rapid prototyping

4. Printed Component Testing

4.1. Setup

Tensile tests of FDM ABS specimens were undertaken in order to assess the consistency of the manufacturing technique and confirm the accuracy of expected structural properties required in the scaling process. Tests were conducted using an Instron 5569 test system with a 5kN load cell and an extension of 1mm/min under uniaxial loading in order to obtain the elastic modulus and ultimate tensile strength of the 3D printed samples.

ASTM D638-02a Type 5 specimens were printed using an Up! Plus 2 printer [19] with the set-up given in Table 1. The layer thickness and air gap are key to the structural properties of the part and were chosen as the minimum possible for the printer in order to ensure parts were as strong and stiff as possible. Raster orientations of uniaxial and ±45° were investigated in this study. The extrusion and envelope temperatures are suited to the material being printed (i.e. ABS) according to the manufacturers printer specifications. Tensile specimens were printed with widths of 3, 5, 7, 9 and 11mm and thicknesses of 5mm; 6 samples were tested for each width and the average structural properties obtained.

Table 1 Up! Plus 2 printer set-up for manufacture of tensile testing parts

Material	ABS
Air gap (mm)	0.5
Layer thickness (mm)	0.15
Extrusion temperature (°C)	270.0
Envelope temperature (°C)	100.0
Specimen design	Dogbone
Poisson's Ratio (*v*)	0.35

4.2. Results

Figure 4 presents the bending stiffness variation with inertia of each specimen width. The gradient gives the Young's modulus of the material as 935.69N/mm^2; this is a 14% difference to the given, pre-printed value, and should be used in all structural scaling calculations. However, it is noted that as the inertia of the component (hence the specimen width) increases.

Some discrepancies in experimental results were due to delamination of the specimen during testing causing failure in the radiused section as shown in Figure 5 for a 7mm sample. This may indicate that a differing design of test specimen should potentially be used with this manufacturing technique and is a topic for further investigation. Some difficulty in achieving dimensional accuracy was experienced due to thermal cooling effects during the printing process. The printing machine used in this work is has an open working section and was therefore open to the effect of drafts within the working environment; this issue can therefore be solved by using an alternative printer type with an enclosed printer bed to maintain constant environmental conditions during printing.

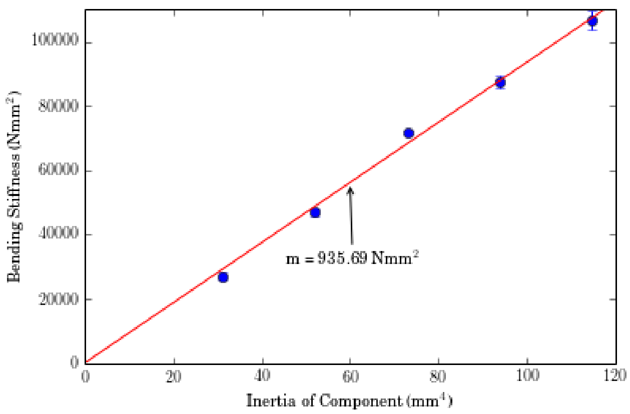

Figure 4 Derivation of Young's modulus for 3D printed ABS samples

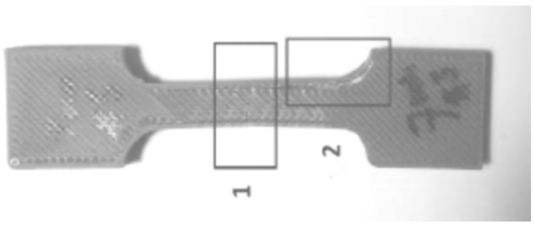

Figure 5 Tensile testing sample showing failure between outer surface and fill layers

Figure 6 presents example stress-strain curves for the 5mm and 11mm width specimens demonstrating that the linear behaviour region and failure mode of the 5mm samples is significantly more consistent than for the 11mm samples. Therefore in order to ensure as accurate a hydro-structural model as possible the ship structure should be printed within model structural integrity constraints found here as well as to meet the appropriate scaling laws.

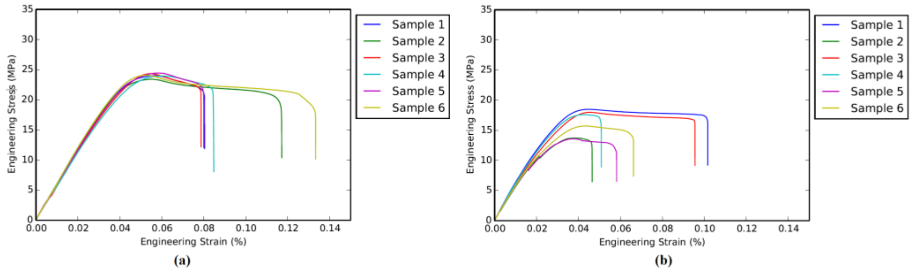

Figure 6 Example stress-strain curves for (a) 5mm width and (b) 11mm width tensile testing samples of 3D printed ABS

5. Printed Hydro-Structural Ship Models

5.1. Block Construction

The finite size of the printer beds requires hydro-structural model to be constructed from a number of sections or blocks. The number of blocks required to construct a model is dependent on the length, breadth and draft (hence the block coefficient) of the model in question. The complexity of the model will increase as the number of blocks increases due to the technical challenges associated with joining the blocks together without compromising the scaled structural properties of the vessel. The total number of blocks, *N*, required for a model hull can be calculated as

$$\boldsymbol{N} = \left\lceil \boldsymbol{C_B} \left(\left\lceil \frac{\boldsymbol{L_{model}}}{\boldsymbol{L_{printer}}} \right\rceil \left\lceil \frac{\boldsymbol{B_{model}}}{\boldsymbol{B_{printer}}} \right\rceil \left\lceil \frac{\boldsymbol{T_{model}}}{\boldsymbol{T_{printer}}} \right\rceil \right) \right\rceil + \left\lceil \boldsymbol{C'_B} \left(\left\lceil \frac{\boldsymbol{L_{model}}}{\boldsymbol{L_{printer}}} \right\rceil \left\lceil \frac{\boldsymbol{B_{model}}}{\boldsymbol{B_{printer}}} \right\rceil \left\lceil \frac{\boldsymbol{D_{model}} - \boldsymbol{T_{model}}}{\boldsymbol{T_{printer}}} \right\rceil \right) \right\rceil \qquad (8)$$

where C_B is the Block coefficient for the underwater hull form and C_B' the equivalent for the above water hull form.

For an example hull of a typical naval frigate with the principal particulars in Table 2, the number of blocks required to manufacture models between 2.0m and 6.0m in length was investigated assuming the printing envelope allowed the ship structure to be split into blocks with maximum dimensions of 100mm x 100mm x 130mm and that no allowance was made for joining methods between the blocks. Results are presented in Figure 7 for three different alignments of a block on the printer bed.

Figure 7 demonstrates that as the length of the model increases the number of blocks required to build it also increases; significant jumps in the trends of the graph are where either the breadth or depth becomes a further order of magnitude greater than the size of the printer bed, with an increase in depth resulting in the most substantial jump. The direction in which parts are chosen to be aligned on the printer relative to the dimensions of the model affects the number of blocks required; further the optimum direction of alignment varies as the length of the model increases. For example, for the 6m model it is optimal to align the draft of the ship along the longest (0.13m) dimension of the printer test bed and the length and breadth of the ship along the shorter (0.1m) dimension; however this is not the case for a 5.5m model.

Table 2 Principle particulars of test hull form

Length overall (m)	113.40
Length between perpendiculars (m)	109.72
Breadth (m)	12.36
Draft at amidships (m)	4.19
Displacement (tonnes)	2921.0
LCG aft amidships (m)	3.96
Service Speed (kts)	18.0
2-node bending natural frequency (rad/s)	14.69

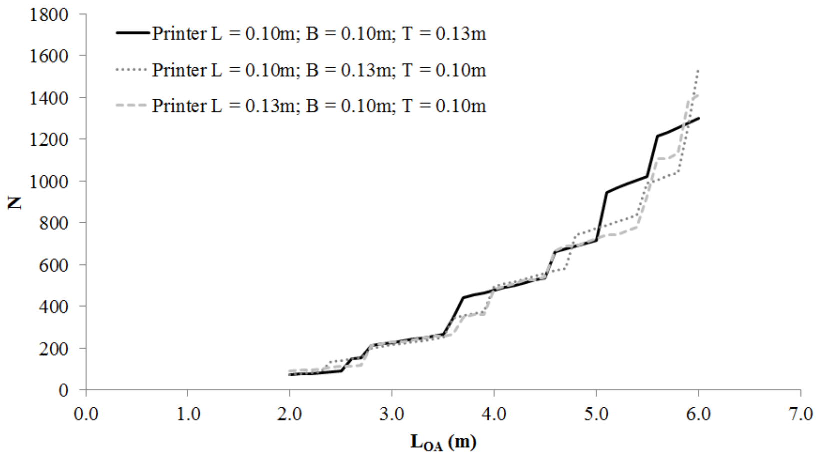

Figure 7 Investigation of block number requirements with model length

It should be noted that for this study, a relatively small printer test bed size was used in order to demonstrate the key relationship between model size and number of blocks; increasing the printer envelope size through using a larger printer bed will result in a substantial reduction in the number of blocks required and hence reduce the technical complexity of joining the model together.

A potential advantage to the block construction system in that there is considerable scope for interchangeable bow and stern configurations to be easily investigated by removing or modifying the blocks for these sections. A key issue then becomes detailed consideration of the method of joining the block together in order to minimise the impact on the hull girder responses, the structural strength and easily allow section changes to occur. Initial studies are currently underway considering glued and mechanical connections. This is an area that will be critical to the success of the process as hard corners and modification of the hull girder stiffness properties due to the joints will need to be avoided.

5.2. Plate Scaling to meet Global and Local Hydroelastic Requirements

Initial calculations of the scaling of a section of plate structure of the frigate hull detailed in Table 2 and with the midship section illustrated in Figure 8 have been performed to investigate the practicality of accurately modelling the ship structure using rapid prototyping and ABS. The structure scaled was a section of deck consisting of 5 plate sections and 6 T-sections. Scaling was conducted using the relationships given in Section 3.

The scaled global and local properties for the frigate hull are presented in Tables 3 and 4, including accounting for the different Young's modulus and Poisson's ratio at model and full scale. Initial calculations used a scale of 1:43.62 (L_{OA} = 2.6m) to correspond to a segmented model at this scale which already exists [2], giving the potential for a smaller section of the vessel to be replaced with a 3D printed section during this research. For comparison results for a model scale of 1:18.9 (corresponding to L_{OA} = 6.0m) are also shown.

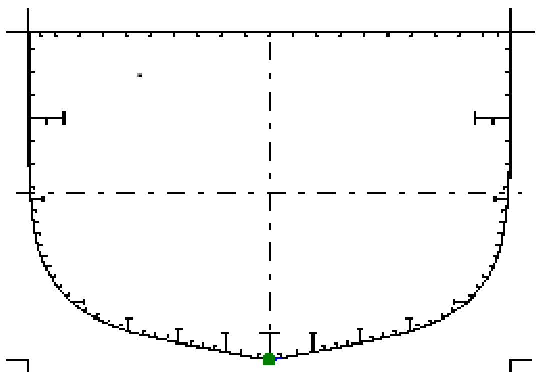

Figure 8 Frigate hull midship section

Table 3 Scaled global properties of frigate hull

	Ship	Model (λ = 18.90)	Model (λ = 43.62)
L_{OA} (m)	113.4	6.0	2.6
EI (Nm^2)	2.02E+12	835952.30	12766.22

Table 4 Scaled local plate thicknesses of frigate hull

	Ship	Model (λ = 18.90)	Model (λ = 43.62)
t (mm)	10	1.04	0.34
t (mm)	6	0.63	0.21
t (mm)	3	0.31	0.10

It can be seen from Table 4 that the plate thicknesses at a model scale of 1:43.62 are not achievable with the printing technologies used to date which have a minimum printable thickness of 1mm. A model scale of 18.9 increases the plate thicknesses but they are still thin enough to make construction difficult. However it should be noted that the frigate illustrated here is a slender, lightweight vessel. Use of 3D printing may prove more practical for either larger scale models or heavier ship structures. Alternatively, a different printing material may prove more suitable and this is something that should be investigated further. The practicalities of handling a model and fitting sensors to it during testing must also be considered.

6. Conclusions

Rapid prototyping techniques provide opportunities to manufacture new and complex geometries that have previously been extremely difficult to achieve. It is a powerful tool that is yet to be fully exploited in the marine industry. The ability to manufacture a realistic ship structure from materials of different properties has the potential to allow new model manufacturing paradigms to be explored. The focus of this paper is the initial findings from an investigation of the use of 3D printing technologies for manufacturing structurally accurate flexible towing tank models. A detailed assessment of the material properties of 3D printed materials and their ability to model the scaled structural behaviour of a ship has been carried out. Scaling implications when considering the realistic ship structure are presented and practical considerations for the construction of 3D printed towing tank models are discussed.

The cost of a printed rigid model currently exceeds the cost of an equivalent rigid model created using traditional manufacturing approaches. However they do provide opportunities to create more complex shapes which provide new opportunities when considering the coupled fluid structural response of a ship. Entry level printers can have low dimensional tolerance due to deformation of the part associated with internal stresses due to thermal cooling resulting in a large variation in the structural properties between parts. The form of rapid prototyping used within this initial study does not lend itself to the creation of isotropic components and it is considered that alternative techniques and materials should be investigated as part of further studies. The constraints imposed by the currently available size of the printer bed results in the need to develop a modular approach to the construction of a large ship model. This has significant implications as to how these sections are then joined together in a suitable manner. Further investigations into the long term effect of ageing on the performance of 3D printed materials in the marine environment are also needed in order to develop a fully rounded understanding of the structural properties. Clearly, this work is an ongoing area of research and one that has merit for future developments.

Acknowledgments

This project is partially supported by funds from the Lloyd's Register Foundation, through the University Technology Centre in Ship Design for Enhanced Environmental Performance at the University of Southampton.

References

[1] S.S. Denchfield, An Investigation into the Influence of Rogue Waves on a Traveling Ship, University of Southampton, UK, 2011.
[2] S.S. Bennett, D. a. Hudson, P. Temarel, Global wave-induced loads in abnormal waves: Comparison between experimental results and classification society rules, J. Fluids Struct. 49 (2014) 498–515. doi:10.1016/j.jfluidstructs.2014.05.009.
[3] I. Drummen, M. Wu, T. Moan, Experimental and numerical study of containership responses in severe head seas, Mar. Struct. 22 (2009) 172–193. doi:http://dx.doi.org/10.1016/j.marstruc.2008.08.003.
[4] D. Dessi, R. Mariani, Analysis and Prediction of Slamming Induced Loads of a High-Speed Monohull in Regular Waves, J. Sh. Res. 52 (2008) 71–86.
[5] J. Lavroff, M. Davies, D. Holloway, G. Thomas, Slamming of High Speed Catamarans in Severe Sea COnditions investigated by Hydroelastic Segmented Model Experiments, in: Proc. 28th Symp. Nav. Hydrodyn., Pasadena, California, USA, 2010.
[6] D. Piro, K.A. Brucker, T.T. O'Shea, D. Wyatt, D. Dommermuth, W.R. Story, et al., Joint High Speed Sealift (JHSS) Segmented Model Tets Data Analysis and Validation of Numerical Simulations, West Bethesda, MD, USA, 2012.
[7] A. Maron, G. Kapsenberg, Design of a ship model for hydro-elastic experiments in waves, Int. J. Nav. Archit. Ocean Eng. 6 (2014) 1130–1147.
[8] Y. Kim, B.C. Kang, Y. Kim, Numerical Analysis and Validation on Ship Springing, in: Proc. 25th Int. Work. Water Waves Float. Bodies, Harbin, CHina, 2010.
[9] S.A. Hong, B.W. Kim, B.W. Nam, Experimental Study on Torsion, Springing, and Whipping of a Large Containership, in: Proc. ISOPE 2011, Maui, Hawaii, USA, 2011.
[10] S. Zhu, M. Wu, T. Moan, Experimental investigation of hull girder vibrations of a flexible backbone model in bending and torsion, Appl. Ocean Res. 33 (2011) 252–274. doi:http://dx.doi.org/10.1016/j.apor.2011.08.001.
[11] I. Watanabe, M. Ueno, H. Sawada, Effects of Bow Flare Shape to the Wave Loads of a Containership, J. Soc. Nav. Archit. Japan. 166 (1989) 259–266.
[12] S.L. Austin, Design History of the Rigid Vinyl Model of the Hydrofoil Plainview (AGEH-1), Bethesda, MD, USA, 1972.
[13] B. Hay, J. Bourne, A. Engle, R. Rubel, Characterisitcs of Hydrodynamic Loads Data for Naval Combatants, Hydroelasticity Mar. Technol. (1994).
[14] International Towing Tank Conference (ITTC), ITTC Recomended Procedures and Guidelines: Model Manufacture: Ship Models, 2008. http://ittc.sname.org/.
[15] C.K. Chua, K.F. Leong, C.S. Lim, Rapid Prototyping: Principles and Applications, in: World Sci., 2003.
[16] G.G. Odian, G. Odian, Principles of Polymerization, Wiley-Interscience, New York, USA, 2004.
[17] M. Montero, S. Roundy, D. Odell, S.-H. Ahn, P.K. Wright, Material Characterization of Fused Deposition Modelling (FDM) ABS by Designed Experiments, in: Proc. Rapid Prototyp. Manuf. Conf. SME, 2001.
[18] R.E.D. Bishop, W.G. Price, On the scaling of flexible ship models, J. Sound Vib. 73 (1980) 345–352. doi:http://dx.doi.org/10.1016/0022-460X(80)90519-2.
[19] Up 3D USA, UP! Plus 2 3D Printer User Manual, (n.d.). http://www.up3dusa.com/.