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Appraisal of topology optimisation and additive manufacturing as tools for developing new joints for modular wind towers

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SUMMARY:
The growth in power and size of wind turbines has pushed the technical feasibility of new projects to the limit by requiring larger supporting structures and complex logistics. Hence, the design philosophy is shifting to lighter, modular towers. However, modularity usually comes at a cost reflected in the number and sophistication of the joints. Therefore, in the scope of the Self-erecting Tower, a prefabricated 'plug and play' device (PnP) is developed to satisfy the requirements of the splice joints between modular panels. The PnP device was designed using structural optimisation techniques and will soon be printed using wired-arc additive manufacturing. In parallel, a sample of specimens will be printed and tested for fatigue, an aspect of great importance in structures subjected to cyclic loading.

Keywords: modular construction, additive manufacturing, WAAM, optimisation, fatigue

1. BACKGROUND AND MOTIVATION

Wind turbines have significantly increased their installed power in the last few years. This enlargement in capacity and size added considerable challenges to the construction of the supporting structures. Larger turbines require more robust, heavier, and reliable towers that can provide the capacity to support the increased loads. Nonetheless, these new supporting structures should also alleviate installation and maintenance costs, ultimately decreasing the levelised cost of energy (LCOE). With the increase in the size of the supporting elements, transportation became an issue, particularly for diameters larger than 4.3 m (Malcolm, 2004). Given these concerns, wind towers are evolving towards systems with lighter components that facilitate manufacturing, transportation, and erection processes. Thus, prefabricated systems that are easy to transport and assemble are now more attractive in the market, such as modular towers, jackets, and lattice towers. Nevertheless, modular construction has more joints than conventional construction methods, many of which have a higher geometric complexity.

This issue opens the opportunity for developing innovative systems that provide solutions to these matters from a practical and scientific point of view. In particular, additive manufacturing (AM) offers excellent versatility, enabling the production of detailed and optimised parts from various materials (Buchanan and Gardner, 2019). Some applications of AM have already been introduced to the wind towers market, improving the design and fabrication of generators (Hayes *et al.*, 2018) and blades (Post *et al.*, 2017). Furthermore, AM has already shown encouraging potential to produce efficient solutions in structural engineering (Lange, Feucht and Erven, 2021). The study of AM materials' fatigue life is still in its early stages, but promising results have been found in the latest research, matching, or even surpassing the behaviour of conventional hot-rolled or forged steels (Li *et al.*, 2022; Ermakova *et al.*, 2023).

In structural engineering, topology optimisation (TO) is evolving into a handy tool and is often used as an opening step before AM. In addition, AM dedicated software already presents the user with the opportunity to blend design and fabrication with the methods and philosophy of digital construction, further contributing to wind energy systems' efficient, sustainable, and high-quality development.

2. METHODS

As a first step, the new joint needs to be developed conceptually. In this work, existing solutions for a modular wind tower (the Self-erecting Tower or SeT) will be re-imagined, considering the possibilities that TO and AM offers. Once the concept is defined, a design space that complies with all geometric requirements is generated. This design space is a volume sufficiently large to accommodate all the optimised material inside. The overturning moment in the wind tower is understood as tensile and compressive loads along its perimeter. Hence, the PnP device should provide a tensile capacity equal to that of the tubular section that hosts it. Once the loads applied are recognised, an iterative process begins to find the optimised shape through TO. A schematic view of the steps described is shown in the figure below using the SeT splice joint.

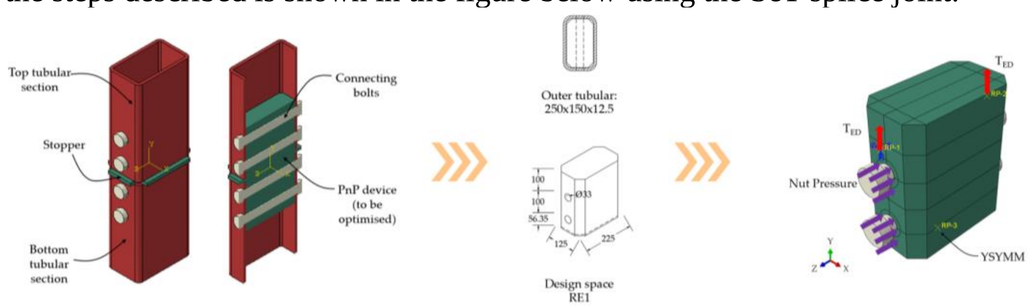

Figure 1. Schematic representation of the (a) conceptualisation stage, (b) definition of the design space and (c) recognition of the loads.

This work has performed the TO using the Tosca Structure integrated into Abaqus/CAE. Two optimisation algorithms are available to the user: condition-based and sensitivity-based. Moreover, for the sensitivity-based algorithm, there are two different material interpolation techniques: solid isotropic material with penalisation (SIMP) and rational approximation of material properties (RAMP). Additionally to the variables mentioned that are directly linked to the optimisation algorithm, other parameters must be specified, such as optimisation function, constraints, mesh and number of cycles.

Several short parametric studies were performed to assess the influence of each parameter on the resultant shape. At first, it was found that the objective function and the constraints were the two variables that had the most significant impact. Hence, using only the sensitivity-based algorithm with SIMP material interpolation technique, C3D8R mesh elements with a maximum size of 10 mm and a constant number of 50 optimisation cycles, different combinations of objective functions and constraints were evaluated, as shown in Table 1.

Table 1. TO cases used to evaluate different results while varying the objective function and constraints.

Variable/Case	RE5-A	RE5-B	RE5-C	RE5-D	RE5-G	RE5-H	RE5-I
Objective function	SE	SE	S	SE	V	SE	SE
Constraint 1	$V_{\%}$	S_{max}	$V_{\%}$	$V_{\%}$	S_{max}	S_{max}	S_{min}
Constraint 2	--	--	--	S_{max}	S_{min}	$V_{\%}$	$V_{\%}$

For the objective function, SE implies a minimisation of the strain energy (i.e., maximisation of the stiffness), S refers to a minimisation of the Von Mises' stresses and V to minimising the volume. In the case of the constraints, single and dual constraints were analysed, in which $V_{\%}$ indicates a percentual subtraction of the original volume; with volumes ranging from 20% to 50%, S_{max} means that no point in the design space can surpass 590 MPa, the ultimate yield strength of the AM feedstock material, and S_{Min} ensures that every point has at least 200 MPa Von Mises stress to ensure that all material is working in some degree. It is essential to highlight that, due to the nature of the optimisation algorithms, the only mechanical property considered during the TO is the Young's Modulus. Hence, the material is modelled as linear elastic up to this point. A new finite element model must be created using plastic material properties to verify that the final shape has greater strength than the hosting tubular section of the SeT. In this case, the results from (Tankova *et al.*, 2022) were used as a reference for the numerical material modelling.

3. DISCUSSION

The short parametric studies revealed that many variables do not significantly influence the final shape of the PnP device. This was concluded after comparing the shapes of each case and their ultimate tensile resistance. The statement is valid for the parametric studies that involved the type of algorithm (sensitivity vs condition-based), the material interpolation technique (SIMP vs RAMP), the mesh size and the number of optimisation cycles.

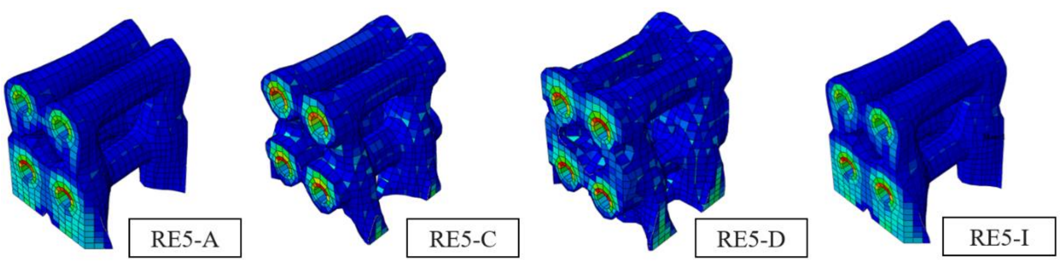

Figure 2. Topology optimisation outputs for cases using $V_{\%}$=20%.

Regarding the objective function and constraints, cases RE5-B, RE5-G and RE5-H gave unworkable results. It was discovered that the optimisation stops too quickly due to some nodes around the bolts and boundary conditions reaching concentrated local stresses over 590 MPa. On the other hand, cases RE5-A, RE5-C, RE5-D and RE5-I produced relatively similar shapes with comparable tensile resistance (Figure 2). However, RE5-I performed slightly better due to the additional constraint that forced every node to have a minimum Von Mises stress of 200 MPa. Also, the plastic analysis of the optimised shapes showed higher resistance than expected. This was confirmed after comparing the tensile resistance of the optimised shapes with pre-defined reference joints that have also been analysed for the SeT case study (i.e., continuous butt welding, plates with bolts in shear and the use of the entire volume for the PnP device).

4. CONCLUSIONS AND FURTHER WORKS

The following conclusions were reached after exploring the influence of different parameters on the results of the TO:

1. For the design space studied, no significant differences were found between the two optimisation algorithms explored, the two material interpolation techniques, the mesh size, and the number of optimisation cycles.
2. Local stress concentrations make it challenging to use maximum allowable stress as a constraint and induce a premature stop of the TO.
3. Even though many combinations and alternatives can be used as objective functions or constraints, the traditional case in which the strain energy is minimised and subjected to a percentual reduction of the volume is the most reliable.
4. The results of the plastic analyses using the AM material properties suggested that the performance of the PnP device is highly superior to that of traditional solutions, proving that the combination of TO and AM can give a good solution for the SeT splice joints.
5. TO and AM demonstrated remarkable versatility, appearing like logical options for developing new bespoke joints for steel construction, especially in modular structures.

Existing research suggests that the fatigue performance of AM materials produced by WAAM is comparable to that of hot-rolled or forged counterparts. Hence, in the following stages of this project, fatigue coupons will be produced from an AM wall resembling the PnP device's printing conditions to assess the fatigue life for this new innovative splice joint.

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