

## Thermoplastic Composites In Sustainable Construction

*Topology optimisation and additive manufacturing for a recyclable and modular building system*

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**Abstract.** Despite the significant environmental impact of the building sector, sustainable building practices are yet to be widely adopted. This paper describes a practical approach based on computational design and additive manufacturing (AM) to generate modular and structural walls, following design for disassembly and recyclability principles. In this research, the anisotropy of recyclable short-fibre reinforced thermoplastic (SF RTP) composites is utilised. The proposed methodology involves starting from the building's topology and using topology optimisation (TO) as a form-finding tool in the design of structural wall modules. The finite element analyses (FEA) guiding the TO are based on conventional building-codes used for load calculations. The TO-defined modules are then further optimised in stiffness by matching the principal stress directions with the AM printing path. Two case studies, the ground floor of a 3-storey building and a bus shelter, are used to illustrate the outcome of the approach. This comprehensive workflow generates structural elements with built-in optimised and tailored performance while enabling unique geometries that combine structural efficiency with architectural creativity.

**Keywords.** Short fibres, Thermoplastic Composites, Structural Optimisation, Additive Manufacturing, Structural Building Design, Modular Construction

### 1. Introduction

Technological advancements in design optimisation and materials science can be leveraged to mitigate environmental impacts and favour circular economy practices in

the building sector. Short fibre reinforced thermoplastic (SFRTTP) composites have high strength-to-weight ratio and can be reprocessed multiple times, depending on the nature of the matrix and the fibre, while keeping consistent mechanical properties (Pegoretti, 2021). Overall, the recycling content of SFRTTP composites can involve the following scenarios: reprocessing of the SFRTTP composite material (i.e. recycling of both matrix and fibres together); SFRTTP composite formulations with recycled polymers as the matrix; or SFRTTP formulations with recycled fibres as the reinforcement (Pegoretti, 2021).

While conventional manufacturing processes for SFRTTP composites such as injection moulding, compression moulding or pultrusion can deliver mass production capabilities for SFRTTP parts, additive manufacturing (AM) is an emerging manufacturing field allowing for several distinct advantages e.g. high design creativity and flexibility, low concept-to-product turnaround and rapid prototyping potential (Ramesh et al., 2024). Several AM technologies for composites exist, with material extrusion-based AM being one of the most widespread AM techniques. The anisotropy induced by AM can be exploited with fibre-reinforced composites as the fibres are generally aligned with the direction of extrusion (Yan et al., 2023). Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the main polymers used in AM due to their processability but a wide range of other polymers such as polyethylene terephthalate glycol (PETG) and polyamides (PA) has become commercially available (Spoerk et al., 2020). Fibres used for SFRTTP can be divided into synthetic fibres (e.g. carbon, glass, Kevlar, basalt) and natural fibres (e.g. hemp, jute, ramie, flax, sisal). Combining the above-mentioned fibres with polymers significantly improves the mechanical properties of the base polymer (Saroia et al., 2020), thus making it an active field of research.

Fibre-reinforced polymer composites' mechanical properties will be dependent on both the mechanical properties of the polymer matrix and of the fibre reinforcement, as well as the fibre/matrix interfacial bonding and the orientation of the fibres in the matrix. For SFRTTP composites, the complex interaction between manufacturing method, fibre distribution within the matrix and the mechanical behaviour of the constituents has spurred research on predicting more accurately the mechanical properties of the overall composite (Li et al., 2021; Mentges et al., 2023). Modelling methods involve computational homogenisation methods based on numerical modelling (e.g. finite element analysis (FEA)) of the representative volume element (RVE), by which computationally determined properties can be extrapolated to the overall composite (Breuer & Stommel, 2020).

The theory of topology optimisation (TO), the application of which can rely on FEA modelling today, has gained momentum as a design optimisation tool for engineering (Sigmund & Maute, 2013), including structural building applications (Goli et al., 2021; Yu Li et al., 2023; B. Zhao et al., 2023). Topology optimisation has the potential to reshape structures or products and optimise their material distribution concerning a specific physical, thermal, mechanical or combined load case. The designer who successfully incorporates TO in the design process can develop products optimised for performance (Tyflopoulos & Steinert, 2020). Topology optimisation is commonly used with AM as a computational tool to generate the optimal material distribution within a certain design domain and under pre-defined boundary conditions

and loads. In the past decades, TO has been an expanding field as a means to computationally determine the optimal, yet not always apparent, solution for a given physical problem, ranging from structural cases to heat transfer or even multiphysics problems (Yago et al., 2022). TO computational approaches developed over the years include: density-based approaches (i.e. solid isotropic material with penalization (SIMP) method), evolutionary methods such as evolutionary structural optimisation (ESO) and bi-directional evolutionary structural optimisation (BESO), level-set techniques, and others (Sigmund & Maute, 2013; Yago et al., 2022).

When it comes to anisotropic materials such as SF RTP composites, the optimisation can be two-fold: the optimisation of the part topology and the optimisation of the material orientation for the load path and distribution within the part. This can be referred to as multiscale TO (Wong et al., 2023). TO of polymer composite parts commonly fall into sequential or concurrent optimisation of material orientation and part topology (Brown et al., 2022; Wong et al., 2023), and both approaches have been researched over the past years. Sequential multiscale TO of polymer composite parts consists of a two-step approach: the topology of the design domain is optimised based on conventional TO algorithms and isotropic properties determined analytically or numerically, while the optimal material orientation is determined in a post-TO step (e.g. by aligning the material orientation with the principal stress directions on the topologically optimised part). Concurrent multiscale TO simultaneously optimises the topology and the material orientation (Ranaivomiarana et al., 2019), for example, by optimising the fibre angle distribution within the part or determining the optimal lay-up sequence of composite laminates. While concurrent multiscale TO can result in higher stiffness for multi-load cases (Nomura et al., 2016), the increased computational cost may not be worth the structural benefits when comparing with sequential multiscale TO (Brown et al., 2022). Nevertheless, both multiscale TO approaches have been used in the literature in combination with AM and an appropriate AM extrusion path algorithm (Wong et al., 2023) for a given load path definition (S. Zhao et al., 2021). However, the literature on TO mostly refer to simple case studies (e.g. cantilever beams or 3-point bending tests) rather than real-world applications. Multiscale TO of SF RTP products manufactured through AM has yet to be incorporated in a comprehensive product development framework (Wong et al., 2023), especially for a building system.

The purpose of this study is to investigate a new structural design methodology based on TO as a form-finding tool and AM as a manufacturing method for the development of an SF RTP building system. It involves investigating the structural potential (i.e. load-bearing and bracing capacity) of recyclable SF RTP materials for building applications, based on the relevant building standards in effect (e.g. New Zealand standards for this study). The innovative building system relies on a TO-defined self-braced module that is 3D-printed and repeated to compose the building's structural walls. By generating a printing path aligned with the principal stress directions of the structural modules under load, AM of the modules ensures that both topology and material orientation are produced as designed in multiscale TO. The reliance on such repeated modules has several implications: it allows for a tailored structural performance for a given building typology; and it enables the possibility of reuse and adaptability in future buildings under similar loading. The use of SF RTP as

the structural material also allows for end-of-life recycling, if reuse is not possible.

## 2. Methodology

The proposed design framework (see Figure 1) is a practical engineering approach to generating structural SFRTP wall modules. Using the mechanical properties of the SFRTP material and architectural information of the building (e.g. location, dimensions, number and size of openings) as main inputs, the proposed design-to-manufacturing workflow outputs structural wall modules repeated and bolted together to form the wall structure of the building. By relying on sequential multi-scale topology optimisation for structural form-finding, the SFRTP modules' performance is inherently tailored to the building case at hand. The methodology relies on commercial computational tools (i.e. ANSYS R1 2024 for FEA and TO simulations, Solidworks for CAD modelling). Two case studies were considered: a 3-storey medium-density housing (MDH) building composed of two adjoining units and a bus shelter. Wind actions for both structures were calculated using Checkwind 8.1.0 with Wellington, New Zealand as the specified location.

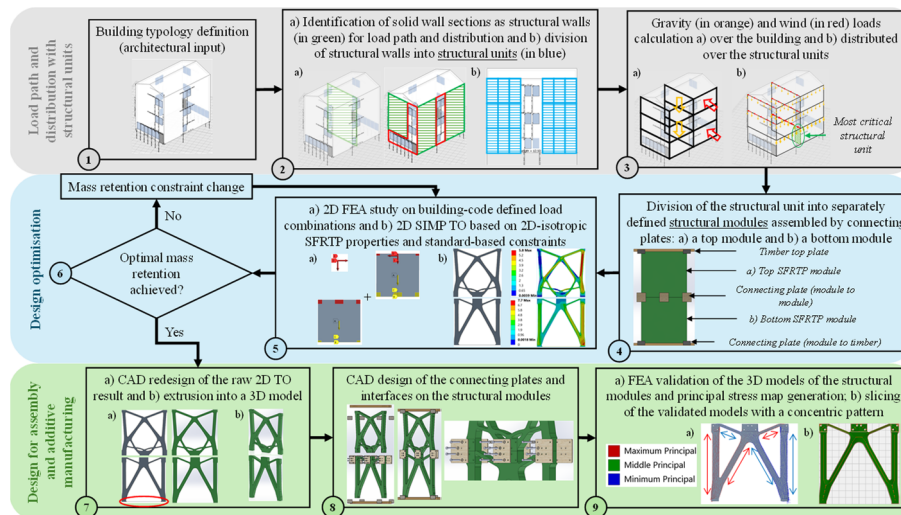


Figure 1. TO- and AM- based methodology flowchart for the design of a modular SFRTTP composite building system

The composites were hemp/PLA SFRTTP formulations of either 20% or 40% in weight of fibres. The composites' properties were modelled on Material Designer, ANSYS R1 2024. The models were prepared for AM (i.e. slicing and G-CODE file generation) using a commercial slicing software (Bambu Studio). The mechanical and morphological properties of hemp fibres produced by alkaline treatment, a standard method for natural fibres, were sourced from the literature (Beckermann, 2007). Isotropic properties for a general-purpose PLA were used as the SFRTTP matrix. While in-plane isotropic SFRTTP properties are used in the TO step of the methodology, the quasi-unidirectional SFRTTP properties were used to model the anisotropy induced by

AM and obtain the final properties of the printed module.

### 2.1. FROM A BUILDING TYPOLOGY TO THE LOAD PATH AND DISTRIBUTION WITHIN THE WHOLE STRUCTURE:

- Step 1: The methodology used in this research is first based on a pre-defined building typology (e.g. single-storey or multi-storey residential building) and geographical location for the construction, as required by the building design standards to determine the applicable gravity, live and wind loads.
- Step 2: Solid wall sections that do not include any openings (i.e. windows or doors) are identified at each floor and represent the structural walls of the building. Wall sections that include openings are considered non-structural. The structural walls are then divided into structural units of identical dimensions that act as the structural members guiding the loads throughout the building.
- Step 3: The loads of the building are then distributed through all the structural units. As they bear the cumulated vertical and wind loads of the floors above, the structural units at the ground floor are selected for the next design steps of the methodology. It is worth to note that the gravity loads of the building would rely on the density of the SF RTP composite, and the assumed final mass of the structural modules after the design optimisation stage. If either the material or the mass of the module changes, the gravity loads must be recalculated before another TO iteration.

### 2.2. TOPOLOGY OPTIMISATION OF SF RTP STRUCTURAL MODULES:

- Step 4: Each structural unit is divided into two modules, the bottom module and the top module, interconnected and assembled to adjacent modules through connecting plates. The SF RTP composite properties are modelled as transversely isotropic in the plane of the wall section. The mechanical properties of the composite can be modelled through analytical modelling or numerical homogenisation techniques. These isotropic properties are only calculated for the 2D SIMP TO stage.
- Step 5: Design optimisation begins by considering the bottom and the top modules as two separate design domains and TO studies. The FEA models from which TO is generated represent the different load combinations prescribed by the applicable building code in the specified region. Load combinations for the ultimate limit states (ULS) and serviceability limit states (SLS) of the structure are modelled as separate FEA load cases. ULS and SLS are differentiated at the TO step through stress minimisation and compliance minimisation objectives respectively. Connections to other modules are integrated in the TO by defining them as fixed areas (i.e. anchor points for the load path) or load application areas; they are thus excluded from the design domain. The TO constraints involve mass retention range, maximum global Von Mises stress (applied as a safety factor in line with the mechanical properties of the material), maximum horizontal displacement at the top of the module and manufacturing constraints (i.e. symmetry and minimum member size).
- Step 6: At this stage, the achievable mass will depend on the building typology, the isotropic properties of the SF RTP material and its density. A change in mass

retention constraint to achieve TO convergence must be reflected in the gravity load calculation, as explained in step 3.

### 2.3. DESIGN FOR ASSEMBLY AND MATERIAL OPTIMISATION THROUGH ADDITIVE MANUFACTURING:

- Step 7: The final 2D TO result is then used as a template for the structural modules' design in CAD. At this stage, any artefact from the TO can be excluded and the overall TO geometry can be smoothed for design for manufacturing. The redesigned 2D geometry is then extruded in the direction of the printing plane.
- Step 8: Connection details are implemented in CAD and included in the design of the structural modules. For this study, a system of plates and bolted connections ensures the structural link between the bottom and top modules, as well as with adjacent modules.
- Step 9: Once the CAD design of the structural modules is finished, the final three-dimensional modules are assessed in FEA using the same initial loads and boundary conditions in step 5. The principal stress directions are extracted from these models and are used to determine the printing path when slicing the structural modules for AM. This post-TO step ensures the optimisation of the material orientation by aligning the material extrusion path of the AM process with the in-plane principal stress directions using a concentric toolpath pattern. For multiscale TO of SF RTP structures, it was found that a concentric toolpath pattern can match the principal stress vector field of the TO result (Brown et al., 2022), hence the same pattern is used in this methodology.

### 3. Results and Discussion

The proposed methodology was applied to the design of load-bearing self-braced wall modules for an MDH building and a bus shelter, as seen in Figures 2 and 3 respectively. In the case of the MDH building, actionable TO results were obtained with few geometrical artefacts. Figure 2 shows the design potential of the methodology: while full solid structural walls can be designed using the same structural modules, the same methodology can be used to address irregular sections of the walls containing openings (e.g. windows or doors). As such, the proposed design methodology allows for the

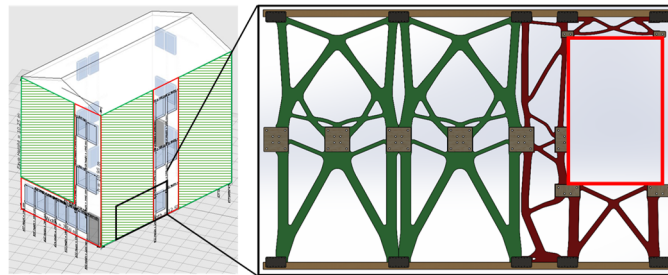


Figure 2. Assembly of a 3-storey MDH building wall section with structural modules (green bodies) and non-structural modules supporting a window (red bodies and red frame)

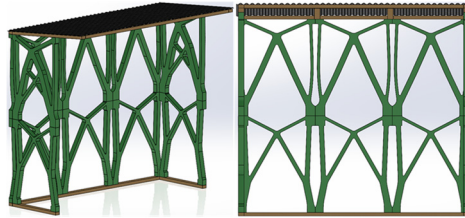


Figure 3. SF RTP modular structure of a bus shelter with a conventional roof

local adjustment of the load path around these openings. For the bus shelter in Figure 3, the loads involved are significantly lower than for the MDH building, resulting in lower structural demand and modules that can be further reduced in mass (either through a lower thickness or with a lower mass retention constraint). As the bus shelter is an exposed structure, the unusual TO design can be revealed to end users as part of the architectural value of the structure.

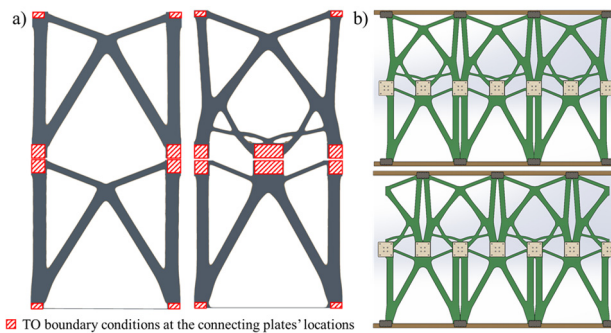


Figure 4. a) Influence of the number of connections involved in TO and b) the possible assembly configurations when adding a central connecting plate between the bottom and top modules

Following the same proposed methodology illustrated in Figure 1, the number and/or location of connections between structural modules can be leveraged to achieve different structural shapes while maintaining the required structural performance, which can be of architectural value for e.g. pavilions or other exposed structures of low structural demand. The number of connections used between modules relates to the load path from one module to the next, thus affecting the structural optimisation and the final optimised geometry of each module (see Figure 4.a). Modular walls with a central connecting plate between top and bottom modules have an additional assembly configuration (i.e. the staggered assembly pattern illustrated in Figure 4.b) that can provide different aesthetics to the structure. However, further research is needed to assess the influence of the assembly configuration on the wall's structural performance.

In sequential multi-scale TO, the last step is the optimisation of material orientation. In the proposed methodology and based on the literature (Brown et al., 2022), the principal stress directions are matched with a concentric printing pattern (Figures 5.a and 5.b), resulting in an approximate alignment of material deposition with the maximum or minimum stresses. In Figure 5.c, the material orientation induced by the printing path was reproduced in FEA by dividing the structural module into sections of

quasi-unidirectional orientation based on Figure 5.b. The difference in structural performance between modules with isotropic properties or quasi-unidirectional properties has been assessed for SF RTP formulations with 20% and 40% fibre mass fractions. Increasing the fibre mass fraction in the SF RTP formulation results in a decrease of maximum deformation in the X-axis from 3.4mm (Figure 5.d, left) to 2.3mm (Figure 5.e, left), as well as the deformation throughout the module based on the coloured maps. In both cases, the modules with AM-induced mechanical properties result in a decrease of the horizontal deformation compared to modules with isotropic mechanical properties, thus resulting in a higher stiffness. However, with 40% fibre mass fraction, the decrease in horizontal deformation (or the increase in stiffness) is proportionally higher than for the case with 20% fibre mass fraction. FEA can be used to estimate the structural advantage of a module strategically printed. Moreover, it implies that the higher the fibre content of the SF RTP material, the more advantageous the proposed material deposition strategy can be for the structural performance of the printed module. This shows the potential of using AM as the manufacturing means to enable the material optimisation step of the multi-scale TO design methodology.

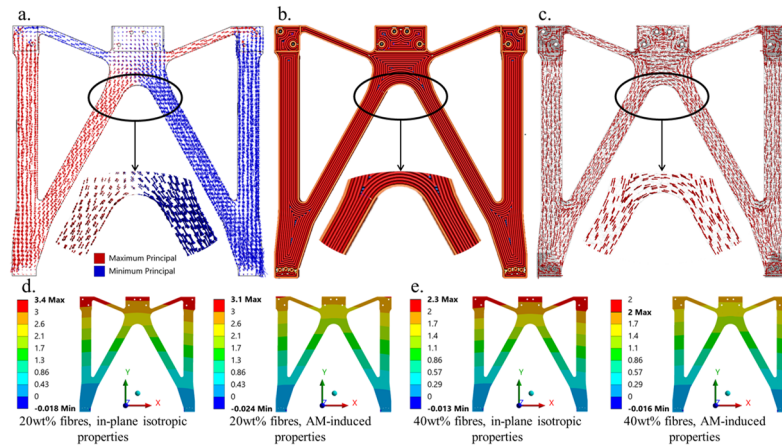


Figure 5. Stiffness improvement strategy of the SF RTP structural module by matching a) principal stress directions to b) the AM printing path. c) FEA validation setup of AM-induced material orientation. Comparative results (deformation in mm in the X-axis) for SF RTP composites with d) 20% and e) 40% fibre mass fractions with isotropic or AM-induced material orientation

With TO as the basis for the determination of the structural performance of the building elements, the proposed methodology relies on the designer adhering to TO shape for the design of the structural modules. By doing so, the designer's work on structural form-finding of wall elements is highly facilitated, but their participation is nevertheless essential in the workflow: the raw TO results must be analysed carefully for any geometrical inconsistencies and, if the location of the connections must be defined before the TO, the connection detailing (e.g. thickness of the connecting plate, number and type of bolts) is entirely dependent on the designer's choices. Instead of fully delegating structural design to computational design programs, the proposed methodology joins the academic endeavour in integrating TO in the structural design process of modular structures (Kazakis et al., 2017; Wang et al., 2023) by proposing a

design-to-manufacturing workflow where initial form-finding stems from TO.

#### 4. Conclusion and Future Works

The design methodology of this research unlocks the potential of combining SF RTP composites as a building material with TO and AM as the design and manufacturing techniques to generate an optimised modular and novel building system. Different SF RTP formulations will yield different TO results/geometries with a different final mass for the module. Although different SF RTP materials have different properties, the same methodology can be used to produce structural elements for the same architectural case study. This has positive implications that need to be investigated: SF RTP composites with higher mechanical properties will yield lighter modules for a targeted structural performance, but essentially, the question of which SF RTP formulation is or is not applicable shifts to a question of material efficiency.

Using a sequential TO approach provided actionable results, but further research should involve concurrent optimisation of topology and material anisotropy to determine its material efficiency and structural performance for buildings. Further work will involve prototyping of the modules and experimental testing of their structural performance under horizontal and vertical loads, with and without strategically AM-induced material orientation. Finally, the environmental implications of using different SF RTP formulations (e.g. with recycled polymer and/or natural fibres) and the end-of-life options enabled by deconstruction (e.g. reuse or recycling of the modules) should be assessed through Life Cycle Assessment.

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