TOPO-JOINT

Topology Optimization Framework for 3D-Printed Building Joints

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Abstract. Joints and connectors are often the most complex element in building assemblies and systems. To ensure the performance of the assemblies and systems, it is critical to optimize the geometry and configurations of the joints based on key functional requirements (e.g., stiffness and thermal exchange). The proposed research focuses on developing a multi-objective topology optimization framework that can be utilized to design highly customized joints and connections for building applications. The optimized joints that often resemble tree structures or bones are fabricated using additive manufacturing techniques. This framework is built upon the integration of high-fidelity topology optimization algorithms, additive manufacturing, computer simulations and parametric design. Case studies and numerical applications are presented to demonstrate the validity and effectiveness of the proposed optimization and additive manufacturing framework. Optimal joint designs from a variety of architectural and structural design considerations, such as stiffness, thermal exchange, and vibration are discussed to provide an insightful interpretation of these interrelationships and their impact on joint performance.

Keywords. Topology optimization; parametric design; 3d printing.

1. Introduction

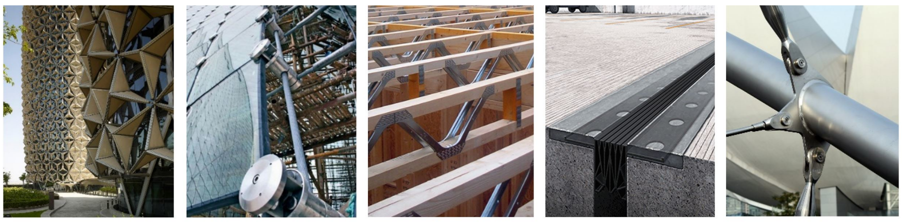
Joints and connectors are among the most critical components that affect the overall performance of building assemblies and systems. This is because these components are often the most complex element in an assembly regarding geometry, functional requirement, and detailing. Many of the mechanical failures occur at joints as the stresses, loads, vibrations, and movements tend to concentrate at these locations. A structural connection is commonly exposed to a set of unique factors which makes it practically impossible to create a single joint or connector that can be universally applied to all conditions.

Some of the critical factors include load conditions, the material property of the structural components, and connection types. Metals have been the most desirable

T. Fukuda, W. Huang, P. Janssen, K. Crolla, S. Alhadidi (eds.), *Learning, Adapting and Prototyping, Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018*, Volume 1, 205-214.

material for addressing these factors due to its superior mechanical properties. However, similar to the automotive, aviation and marine industry; the attributes of synthetic composite materials (e.g., light, inert, and durable) have potential to become a viable alternative material for the construction industry. The recent advancement in additive manufacturing (AM) technology is further contributing to this change, particularly for low volume production of highly customized and intricate geometries such as the joints and connectors.

Furthermore, joints and connectors are often the direct sources of undesirable heat and sound transmission (e.g., thermal and acoustical bridge). High-performance building joints and connectors are commonly made of metals which are not only highly conductive regarding heat, but also create and transmit both airborne and impact noise very efficiently. Existing strategies for mitigating the heat, and sound transmission include using bracing, anchoring, or propping to prevent the movement from occurring or insert polymer breaks to reduce the adverse effects (e.g., thermal breaks in fenestration detail). These strategies tend to be more susceptible to failure or malfunction compared to conventional connectors due to its complexity and high tolerance requirements.



(a) (b) (c) (d) (e)

Figure 1. (a) dynamic façade detail (Image © Christian Richters); (b) curtain wall joint detail (Retrieved from http://letsglass.com); (c) toothed timber connector detail (Retrieved from http://trada.co.uk); (d) expansion joint (Retrieved from http://srwaterproofing.com); (e) steel connector detail (Retrieved from http://publicdomainpictures.net).

In this context, this research aims to investigate the potentials of 3d printed topologically optimized hybrid materials as a means to overcome the abovementioned challenges and needs. The primary focus of this paper is to develop a multi-objective topology optimization framework for designing high-performance building joints and connections.

2. Topology Optimization Framework

2.1. TOPOLOGY OPTIMIZATION

The goal of optimization is to find a design solution that provides the best performance of the objective function while satisfying given design constraints. Topology optimization (Bendsøe and Sigmund, 2004) is a mathematical method to find a shape by acting on its topology where the design variable is a material density in a continuum setting or a cross-sectional size in a discrete setting. Therefore, topology optimization determines the best physical size, shape, and connectivity for generating material layouts.

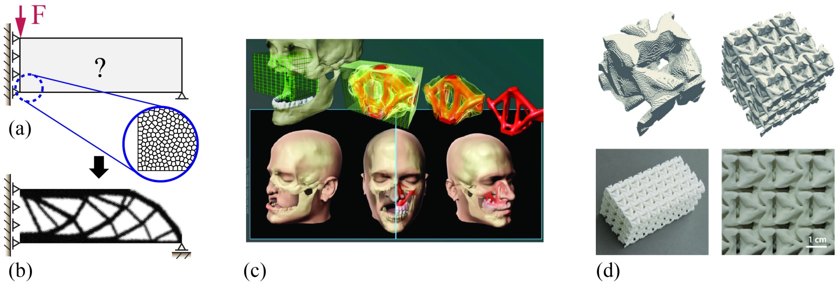


Figure 2. Topology optimization and its applications. Topology optimization process: (a) design prob-lem showing loading and boundary conditions and finite element discretization, (b) optimal topology for maximization of stiffness. Results of topology optimization: (c) optimal topology for craniofacial bone construction (Sutradhar et al., 2010), and (d) unit cell topologies opti-mized for elastic properties (Osanov and Guest, 2016).

Topology optimization has been successfully applied in various fields such as mechanical engineering (Paulino and Silva, 2005), aerospace engineering (Krog et al., 2004), and medical field (Sutradhar et al., 2010). Currently, this approach is progressively transitioning into the structural engineering industry (Chun, Song, and Paulino, 2016; Filipov et al., 2016). Figure 2 illustrates the diversity of design problems and applications of topology optimization. The proposed research strives to link joint designs and detailing intents with the structural performance and manufacturing constraints through topology optimization. The general optimal design problem is stated as follows:

$$\min_{d} f(d,u) \tag{1}$$

$$s.t \quad g_i(d,u) = 0 \ \text{ for } \ i = 1,\ldots,n \tag{2}$$

$$h_j(d,u) \leq 0 \ \text{ for } \ j = 1,\ldots,m \tag{3}$$

Where, f is the objective function; **d** is the design variables, and **u** ≡ **u(d)** is the response, which is related to the equality and inequality constraint functions g_i and h_j, respectively; i and j are the indices of constraint function, and n and m denote the number of constraints. As part of this research, the proposed optimization framework includes various engineering objective and constraint functions; and multi-functional joint analysis and design process.

2.2. ADDITIVE MANUFACTURING

Additive manufacturing (colloquially known as 3D printing) has been making rapid progress through the recent years, overcoming the limitations of speed, resolution, type of materials, and diversification of application fields (Jones et al., 2011). Additive manufacturing is heavily used in the medical, robotics, and aviation industry attributable to its capacity to cope with the demand for highly customized small quantity components. The complexity of the geometry does not add additional cost, and waste produced during the manufacturing process is also less compared to the subtractive manufacturing process. Additive manufacturing continues to challenge the limitations of 3D printing technology through developing high-performance materials that are stronger, more flexible, or tougher. It is now possible to print materials such as metal alloys, glass, conductive ink, heat-resistant materials, ceramics, and nano-materials among many others. Materials with low embodied energy, functional materials, hybrid composite materials, and adaptive materials (e.g., 4D printing) are expected to be the next generation materials that will further advance the capability of 3d printing technology.

2.3. ARCHITECTURED MATERIAL

In this context, there is an interest in exploring the design of architectured (or hybrid) materials (Fleck, Deshpande and Ashby, 2010) to achieve specific mechanical properties using topology optimization and additive manufacturing (Osanov and Guest, 2016). There also have been discussions on several key areas of work related to topology optimization of elastic, thermal, and thermoplastic materials (Cadman et al., 2013). Finally, some speculative and experimental materials research are in progress. These include the research on the properties of fluidic materials (Andreasen and Sigmund, 2011), piezoelectricity (Silva, Fonseca and Kikuchi, 1997), viscoelastic damping (Andreassen and Jensen, 2014), and metamaterials (Zhou et al., 2011).

In the building industry, 3d printing large-scale composite materials such as reinforced concrete have been one of the most significant challenges. With the introduction of reliable metal 3d printing and multi-material 3d printing, the potential for 3d printed composites for buildings is becoming increasingly feasible. Although there are some efforts to combine additive manufacturing and topology optimization techniques (Vil-lanueva and Maute, 2014), further research by the scientific community is necessary to establish a rational framework and processes for implementation.

3. Architectural and Engineering Optimization in Joint Design

Joints are analyzed and designed to satisfy the target performances. They include stiffness for structural connections; heat transfer for architectural façade or wall joints; and vibrational resonance control of members subjected to periodic forces. Also, microscopic material structures of joints can be reconstructed to improve architectural and structural performance. In this section, different optimization objectives are briefly discussed, and optimal results associated with them are presented. The development of a parametric joint design tool presented in Section 4, incorporates architectural and engineering considerations.

3.1. STIFFNESS (STATIC COMPLIANCE)

Building joints such as truss, beam-column, and curtain wall need to have the required stiffness. Using the topology optimization method, the stiffness of joints subjected to multi-directional forces can be maximized with a certain amount of volume. For instance, a joint design domain and boundary conditions are shown in Figure 3(a). The optimized material layout (Figures 3 (b)-(c)) that provides the stiffest structure for the defined set of loads with a certain amount of volume is identified using topology optimization.

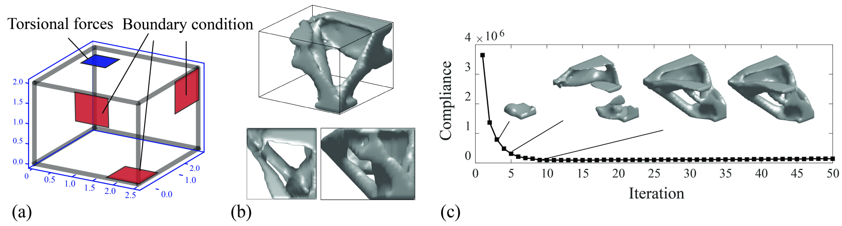


Figure 3. (a) joint design domain, force, and boundary conditions, (b) optimal topology, (c) iteration histories of optimization.

3.2. THERMAL CONDUCTIVITY

Controlling thermal conductivity is crucial in joint design because a significant amount of heat is transferred through joint areas. The exchange of kinetic energy through the boundary between two systems is thermal conduction. When an object is at a different temperature from its surrounding, heat energy flows to yield the same temperature between the body and the surroundings, which is thermal equilibrium. The optimization problem for thermal conduction aims to find the topological material distribution that minimizes the heat compliance. A joint design space is uniformly heated and holds a heat sink such as the low-temperature area (e.g., T = 0) as shown in Figure 4. Optimal topology and temperature distributions between the initial and optimized solutions are shown in Figures 4 (b)-(c).

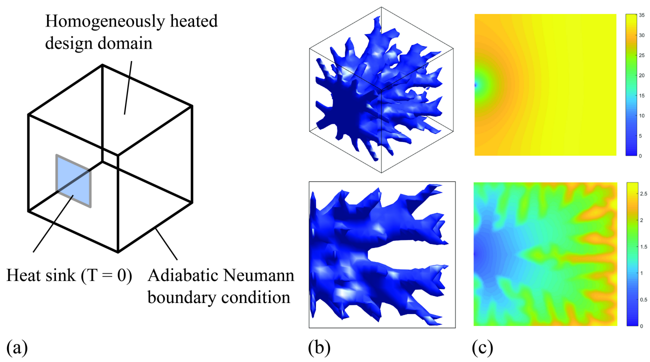


Figure 4. Thermal conductivity optimization. (a) Design domain, (b) optimal topology, (c) initial and op-timized temperature distribution (cut the optimal topology at middle level).

3.3. NATURAL FREQUENCY AND FORCED VIBRATION

Forced harmonic vibrations are significant in practical mechanisms and are frequently encountered in engineering systems. Also, if joints hold objects subjected to periodic forces in a connection design, the dynamic resonance should be carefully checked and avoided. The dynamic resonance is a phenomenon of amplitude oscillation at specific frequencies (e.g., natural frequencies) and occurs when forcing frequencies are close to object's natural frequencies.

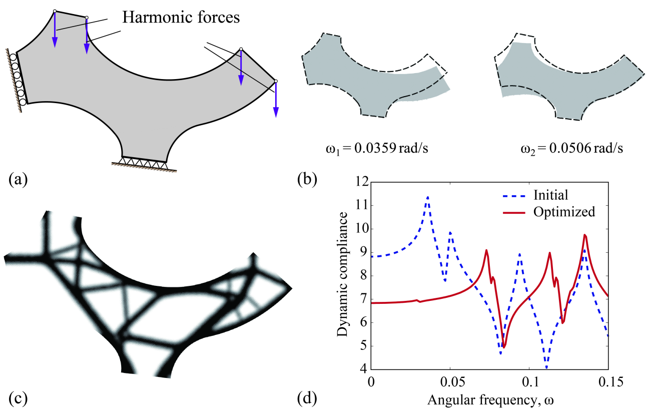


Figure 5. (a) The geometry of joint design domain and loading configuration, (b) normal mode shapes and natural frequencies, (c) optimal topology, (d) dynamic compliance of initial and optimized designs.

Thus, topology optimization problem of the dynamic compliance finds optimal solutions to minimize resonance energy. For instance, the geometry of a curved joint connection domain as shown in Figure 5 is under harmonic forces. The optimal topology of the joint reduces the dynamic compliance as shown in Figure 5(d).

3.4. MATERIAL PROPERTY

Micro-scale material distribution also changes the global mechanical properties of the macroscopic materials (i.e., bulk material). For example, although most of the materials have Poisson's ratios around 0.3, it is possible to have a material with negative Poisson's ratio. A material with the negative Poisson's ratio can achieve low bulk modulus and high shear modulus at the same time and can deliver better performance against impact loads (Park et al., 2015). To achieve the negative Poisson's ratio, the microstructure of the material is designed using topology optimization. Figure 6 shows micro-structure material design targeting the negative Poisson's ratio with a specific volume fraction using topology optimization. Topology optimization utilizing mathematically driven nature leads to alter structural connectivity for high-performance architectural material design and usages in joint-connection design.

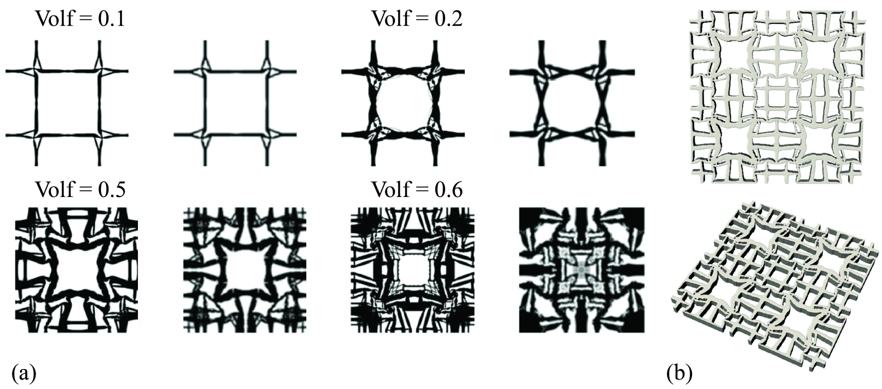


Figure 6. Architectured material design using topology optimization. (a) Optimal micro-structure material distribution, (b) 3D printed micro-structure.

4. The parametric design process and optimization algorithm integration

The building joint optimization framework discussed in the previous section is applied to the development of a structural design optimization tool. This tool aims to provide architects and engineers with a platform for resolving the conflicts between aesthetics, stability, and safety in de-signing building joints. Furthermore, as an integrated visualization platform, this tool will enable professionals to communicate and collaborate effectively with each other to design complex joint-connection design for irregular and non-conventional configurations.

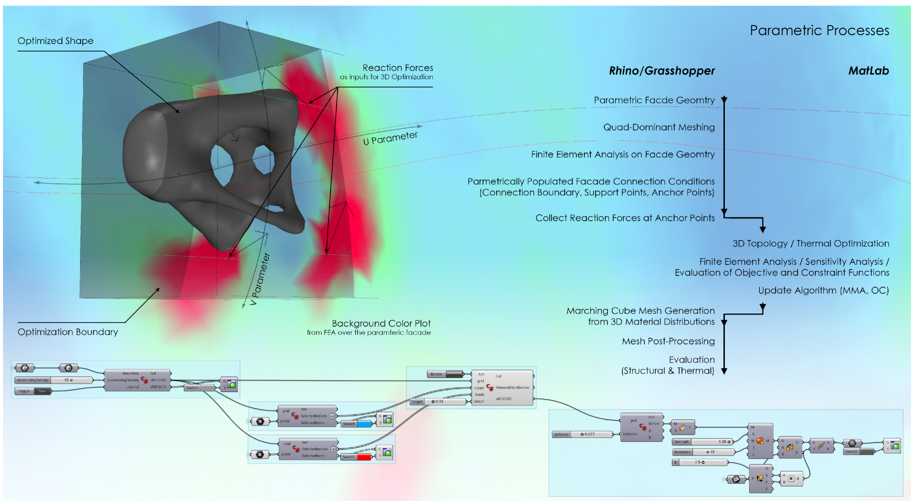


Figure 7. Integrative optimal design framework with algorithmic modeling tool: Optimal joint design through the parametric design process.

The advanced numerical modeling, analysis, and algorithms are developed using MATLAB, and the visualization and interface were developed using Grasshopper 3D. The geometric and parametric variations that architects generate can be implemented in real-time. The practical constraints discussed in Section 3 is also simultaneously reflected in the structural optimization results. Figure 7 illustrates the overall parametric optimization process, and once the final results are obtained using this tool, the geometry can be further refined and post-processed for 3D printing within the Rhinoceros 3D computer-aided design application.

The current version of the tool has the capability of examining geometric configuration, and loading profile; perform finite element analysis, sensitivity analysis, and optimization algorithm; and simple multi-objective optimization (stiffness and thermal conduction) using the Pareto efficiency (see Figure 8). The extension of optimization framework incorporating multiple design objectives in interdisciplinary fields is in progress (e.g., vibration, material property, safety, and structural design code).

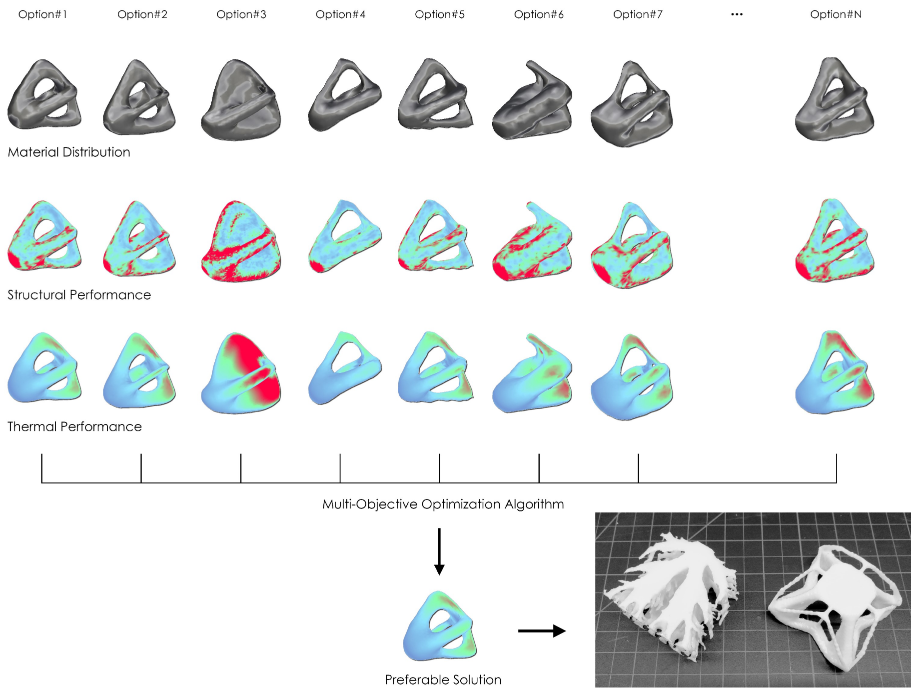


Figure 8. Joint connection optimization and rapid prototyping (additive manufacturing).

5. Conclusion and Further Research

This paper presents the development of a topology optimization frame-work integrating 3d printed non-conventional building materials for creating customized joints and connections for building applications. Significant optimization problems associated with the joint and connection design is described with numerical applications to show the effectiveness of the developed optimization framework. Based on this study, this research also proposes a parametric joint and connection design tool. Using the framework, multiple design solutions satisfying the desirable performances are identified, and evaluations and analysis of optimal topologies are performed to check the feasibility of practical applications. The parametric joint and connection design tool can examine geometric configuration, loading profile, and perform finite element analysis, sensitivity analysis, and optimization algorithm as well as simple multi-objective optimization using the Pareto efficiency. As future research, a robust multi-objective optimization algorithm and analysis approaches need to be integrated into the proposed framework so that interdisciplinary design considerations and constraints can be reflected efficiently in the solution fields.

Acknowledgments

This research has been supported by Syracuse Center of Excellence and Syracuse University School of Architecture.

References

Andreasen, C.S. and Sigmund, O.: 2011, Saturated poroelastic actuators generated by topology optimization, *Structural and Multidisciplinary Optimization*, **43 (5)**, 693–706.

Andreassen, E. and Jensen, J.S.: 2014, Topology optimization of periodic microstructures for enhanced dynamic properties of viscoelastic composite materials, *Structural and Multidisciplinary Optimization*, **48(1)**, 51–66.

Ashby, A.: 2013, Designing architectured materials, *Scripta Materialia*, **68**, 4-7.

Bendsøe, M.P. and Sigmund, O.: 2004, *Topology optimization*, Springer Berlin Heidelberg, Berlin, Heidelberg.

Cadman, J., Zhou, S., Chen, Y. and Li, Q.: 2013, On design of multi-functional microstructural materials, *Journal of Materials Science,*, **48**, 51-66.

Chun, J., Song, J. and Paulin, G.: 2016, Structural topology optimization under constraints on instantaneous failure probability, *Structural and Multidisciplinary Optimization*, **53**, 773-779.

Filipov, E.T., Chun, J., Paulino, G.H. and Song, J.: 2016, Polygonal multiresolution topology optimization (PolyMTOP) for structural dynamics, *Structural and Multidisciplinary Optimization*, **53(4)**, 673–694.

Fleck, N.A., Deshpande, V.S. and Ashby, M.F.: 2010, Micro-architectured materials: past, present and future, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*.

Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C. and Bowyer, A.: 2011, RepRap – the replicating rapid prototyper, *Robotica*, **29(1)**, 177–191.

Krog, L., Tucker, A., Uk, A., Kemp, M. and Boyd, R.: 2004, Topology optimization of aircraft wing box ribs, *AIAA, Multidisciplonary Analysis and Optimization Conference*.

Osanov, M. and Guest, J.: 2016, Topology Optimization for Architected Materials Design, *The Annual Review of Materials Research*, **46**, 211-33.

Park, D., Romo, A. and Lee, J.: 2015, Poisson's Ratio Material Distribution, *Proceedings of CAADRIA 2015*, Daegu, 735-744.

Paulino, G.H. and Silva, E.C.N.: 2005, Design of functionally graded structures using topology optimization, *Functionally Graded Materials*, **VIII**, 492–493, 435–440..

Silva, E.C.N., Fonseca, J.S.O. and Kikuchi, N.: 1997, Optimal design of piezoelectric microstructures, *Computational Mechanics*, **19(5)**, 397–410.

Sutradhar, A., Paulino, G.H., Miller, M.J. and Nguyen, T.H.: 2010, Topological optimization for designing patient-specific large craniofacial segmental bone replacements, *Proceedings of the National Academy of Sciences*.

Villanueva, C.H. and Maute, K.: 2014, Density and level set-XFEM schemes for topology optimization of 3-D structures, *Computational Mechanics*, **54(1)**, 133–150.

Zhou, S., Chen, W., Sun, Y. and Li, Q.: 2011, Topology optimization for negative permeability metamaterials using level-set algorithm, *Acta Materialia*, **59(7)**, 2624–2636.