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FUNCTIONALLY GRADED ARCHITECTURAL DETAILING USING MULTI-MATERIAL ADDITIVE MANUFACTURING

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Abstract. The paper presents a future architectural detailing strategy enabled by the design of functionally graded materials (FGM). In specific, our proposal suggests the possibility of removing mechanical fasteners and adhesives from joint details. This is achieved by combining the principles of interlocking joineries found in traditional timber structures and current Multi-Material Additive Manufacturing (MMAM) technology to materialise FGMs. FGM belongs to a class of advanced materials characterised by variation in properties as the dimension varies by combining two or more materials at a microscopic scale (Mahamood et al. 2012). FGM is ubiquitous in nature and, when properly designed, can exhibit superior performance characteristics compared to objects comprised of homogeneous material properties. With the aim of developing interlocking details with improved performance, reliability, and design flexibility, we focus on controlling material stiffness, joint fitting, and geometry through the design of the microscopic material layout. A case study design will be presented to illustrate the process.

Keywords. Functionality Graded Material; Multi-Material Additive Manufacturing; Architectural Detailing; Interlocking Joints.

1. Introduction

In the past century, structural detail design has been dominated by the use of mechanical fasteners and/or adhesives to connect homogeneous elements of industrial materials like steel and/or concrete. On the contrary, historical heterogeneous timber structures mainly employ the use of interlocking joints in their detailing. Interlocking details can be viewed as a design principle to join and connect multiple individual structural components without the application of mechanical fasteners and/or adhesives. The design of such details involves the various connecting pieces of a structure to have carefully designed geometry and intelligent material usage. Although traditional interlocking joints that have been developed and refined over centuries exhibit an enormous body of material knowledge, its application to buildings are limited today and often requires mechanical fastening. This is because of the multiple factors involved in ensuring the structural performance of interlocking joinery made of natural timber material. The factors include, but are not limited to, moisture content, knot location, grain irregularity, and wood species and growth condition of the timber, as well as the skill level of the craftsman in producing joints with appropriate accuracy and tolerance (Erman 2016).

In this context, our research takes a view that microstructure and its composition of every material, including that of wood, will be designed and custom-tailored to improve its performance and reliability in the near future (Messler 1995; Messler 2000). These materials are called Functionally Graded Materials (FGM) and one of the methods to materialise such concepts is accessible today through Multi-Material Additive Manufacturing (MMAM) technology.

We envision that by designing material stiffness and fitting tolerance, the interlocking joints can be re-introduced into architecture as a viable detail solution with improved performance and reliability as well as with more design flexibility. The paper provides an overview of FGM and related studies with respect to material stiffness/strength and fitting design, followed by a particular case study of furniture design with interlocking FGM details.

2. Functionally Graded Materials

FGMs are characterised by a variation in properties within a single material composition and provide a selective juxtaposition of multiple materials within an object. Through careful design of the material layout, they offer superior mechanical, thermal, optical and chemical properties of their single material homogenous variants of uniform properties (Suresh 2001; Watanabe et al. 2003).

The concept of FGM was first proposed in the 1980s for the Japanese aerospace industry to develop reusable rocket engines that required material to withstand the large difference in internal and external temperatures across a thin cross-section of a thermal barrier. (Sobczak & Drenchev 2013; Udupa et al. 2014). This has given rise to a special class of heterogeneous composite materials which have been engineered to meet practical problems and involve the combination of two or more materials bonded together in the microscopic scale (Mahamood et al. 2012). More recent research trends of FGM have been propelled by the introduction of MMAM which eased its fabrication. Examples include the development of tunable shape memory polymers and alloys, actuators, energy harvesting/generation and recreation or modification of inherent material properties and behavior found in nature and biology etc. (Cutkosky & Kim 2009; Djumas et al. 2016; Ferreira et al. 2016; Ge et al. 2016; Guttag & Boyce 2015; Oxman et al. 2011).

Next, we look into some of these examples that are relevant to the domains of our research: (a) Material Stiffness and Strength and (b) Fitting.

2.1. MATERIAL STIFFNESS AND STRENGTH

Material stiffness, in the design of traditional timber joints, is often physically and visually manifested in the alignment of the timber grain with respect to the loading direction. When applied to FGMs, the act of enhancing the stiffness of materials gives rise to the development of Graded Structural Materials (GSM), which have been widely explored in the fields of material science, engineering and manufacturing (Ren et al. 2014).

In recent literature, von Mises stress is used as criteria for the design of the material composition within FGMs. For Hedia & Mahmound's work, the microstructure of a functionally graded dental implant was designed with respect to local stress distributions in the bone in the vicinity of the implant. Finite element analysis and material optimisation were performed to assign volume fractions and rule of mixtures of the ceramic and metal composition of the FGM implant (Hedia & Mahmoud 2004). Similarly, Wu et al.'s study of the synergetic strengthening of gradient metals used von Mises stress to determine the isotropic strengthening with the complex gradient structure (Wu et al. 2014). This had led to the prediction of the strength of the composition based on the rule of mixture, and subsequently, provide a strategy for designing for such FGMs.

2.2. FITTING

For solid timber joints, the principle of shrink-fitting, a type of interference fitting, is employed by compressing or shrinking one member into another in order to create a contact pressure and friction force at the interface of the two assembled parts. Localised stresses are concentrated at the contact surface of the joint and provide a stiff load path that does not weaken significantly by the shrinking/swelling of the material over time (Wang & Lee 2014). As for other materials, this technique could be performed in the presence of external stimuli, as done in the methods of cold expansion, heating or electromagnetic riveting (Cao & Cardew-Hall 2006; Chakherlou et al. 2009).

To the best of our knowledge, there have yet to be specifically designed FGMs in this field of application. Nonetheless, the use of composites in interference fitting joints has been recognised as an efficient mechanical retention system in terms of weight reduction (Lee & Lee 2005). Lee & Lee's paper demonstrates the use of a laminated composite tube in interference fitting and has performed physical experimentation and finite element analysis to evaluate the localised stress and transmission of the torsional load within the component (Lee & Lee 2007).

3. Case Study: Table Design

Merging the principles of functionally grading materials for material stiffness and fitting, we present a process and our considerations pertaining a table design composed of interlocking joints fabricated using MMAM (figure 1).

The small coffee table is composed of 5 elements connected via interlocking joints without the use of mechanical fasteners or adhesives. The cantilevering composition of the table is designed to illustrate the use of geometry and material to withstand structural loads. Though our focus here is material design for interlocking joints, first, we briefly touch on the overall geometric design - a critical aspect for such detail design.

Figure 1. A Full-scale prototype of the interlocking table. (photograph by Jansen Teo photography).

3.1. GLOBAL GEOMETRY DESIGN FOR INTERLOCKING JOINTS

An interlocking joint and its material design cannot be considered in isolation from its overall structure. Assembly and disassembly directions require careful consideration together with the overall structural integrity. This is because the assembly insertion direction of interlocking joints is the direction in which the interlocking structures cannot transfer loads. The middle joint (Joint A, figure 2) is designed based on a traditional Japanese joinery called Kone-Hozo-Katamuki-Doutsuki. The joint is typically used to connect columns and beams in an orthogonal configuration and is considered good at taking axial compression and bending moment. The geometry of this traditional joint is modified so as to fit the desirable spread angle of the table legs (figure 3). At the same time, the tilt of this assembly set ensures the pull-out force (force acting on the disassembly direction) to be resisted by the ground. The assembly direction of the custom designed top joint (Joint B, figure 2) is near perpendicular to the table top assembly direction. The combination of the perpendicular assembly directions of two elements acts as a lock to prevent disassembly. When considering natural timber as a material for the joint, joint geometry is constraint by the grain orientation. However, as our approach proposes to design the material stiffness and joint fitting, we can achieve the proposed geometric flexibility. The overall design has undergone several iterations of prototyping and Finite Element (FE) Analysis before achieving its final form.

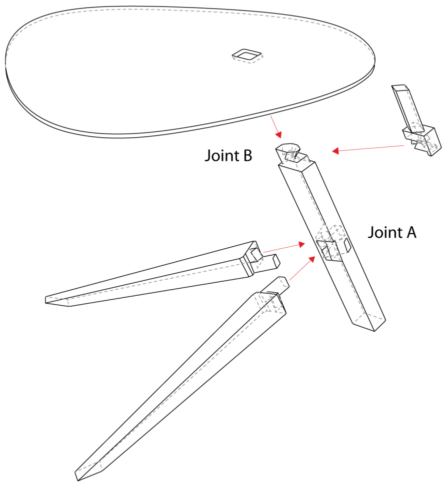

Figure 2. The interlocking table is composed of 5 elements without mechanical fasteners or adhesives.

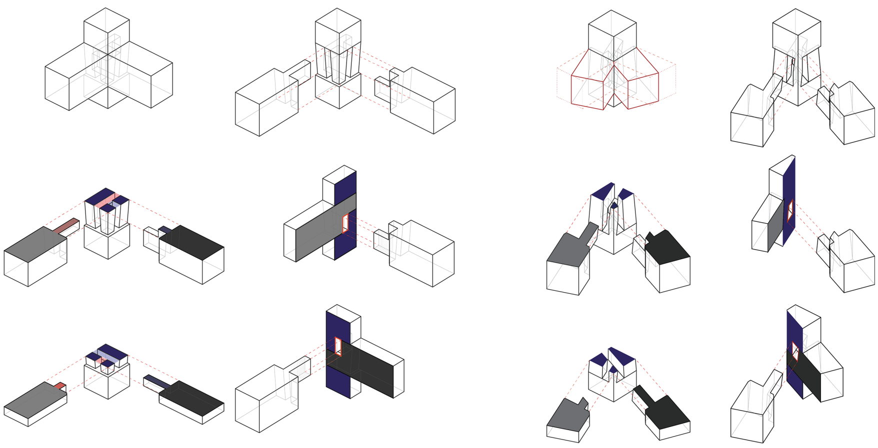

Figure 3. Left two columns: diagrams of traditional interlocking joinery; Right two columns: diagrams of modified joinery structure for the interlocking table.

3.2. DESIGNING FOR MATERIAL STIFFNESS

The FGM design for the table legs (figure 4) was considered following the global geometry design. The scope here is to design FGM/GSM based on full 3D solid contact FE analysis result. In particular, the von Mises stress gradient and principal stress values were used to determine the microscopic material layout using multi-material Voxel Printing, supported by the OBJET Connex 3D printer (OB-

JET). The machine uses PolyJet Matrix Technology where materials are dispensed from designated micro-scale inkjet printing nozzles at approximately 600dpi. The primary materials, excluding the support material, are the Vero and Tango-series where Vero-series materials are thermoset polymers, while Tango-series materials are elastomers. By combining those two very different types of materials, the printer offers the capability of producing objects with varying elasticity. And as such, it is possible to design and prototype structurally graded design solutions. Our method uses Rhinoceros (Robert McNeel & Associates) as CAD modelling platform, ABAQUS (Dassault Systèmes) for FE analysis, a software tool we developed for material modelling based on FE results, and Monolith (Autodesk) for rasterization.

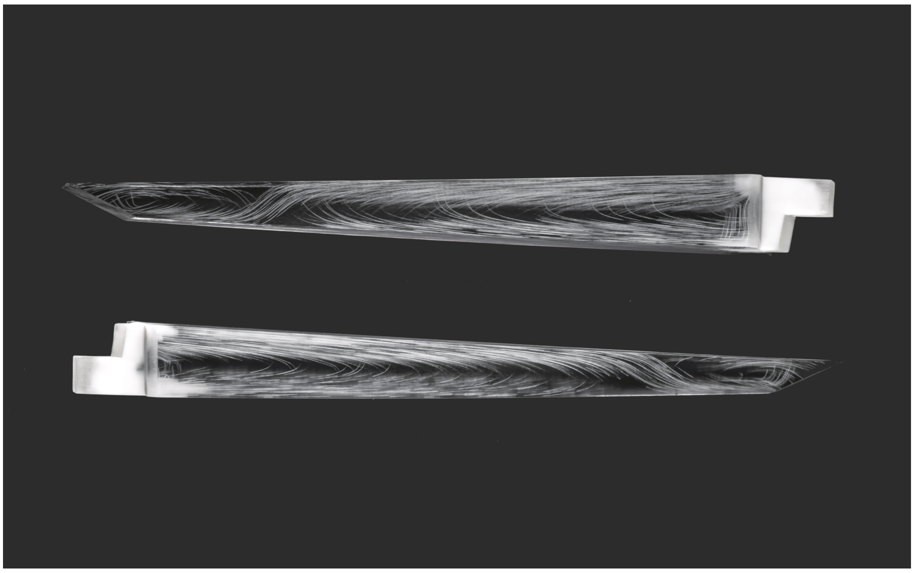

Figure 4. Fully 3D printed FG interlocking table legs with MMAM. White areas indicate the location of stiff material. (photograph by Teo Jansen photography).

As discussed in section 2, the notion of FGM / GSM has been well studied and some of the hardware to materialise the concept is offered by MMAM technology. However, fabrication of FGM for architectural applications is not a trivial task. This is primarily due to the access to the technology being limited by the way in which current modelling and simulation tools represent, exchange, and process information (Jackson et al. 2002). The challenges involved in the computational workflow including the data structure to materialise FGM with MMAM have been discussed in detail in our previous paper through a theoretically well-understood case of a cantilever beam structure (Kaijima et al. 2016).

The initial global geometry, including the table legs, was modelled in a CAD software using the boundary representation (B-Rep). Subsequently, we performed pre-processing operations for FE analysis such as assignment of material properties, loading and boundary conditions as well as discretization of the solid into polyhedral elements. The FE analysis calculation produced results consisting of response values calculated at vertices/nodes and cells/elements (figure 5). Typically, for post-processing purposes, cell results are extrapolated and stored at vertices. This information per vertex becomes the input for the material design step. Each vertex contains positional information as well as any FE result information such as {x, y, z, s11, s22, s33, s12, s13, s23, vm} where s11 to s33 denotes normal stress tensor values, s12 to s23 denotes shear stress tensor values and vm denotes the von Mises stress value. We have overlaid several analysis results of anticipated loading conditions for the table design.

The next step involved Voxelization of the FE results. This is to convert polyhedral mesh structured data into voxels that are a common data structure for MMAM. The step requires the computation of the integrals over the intersection volumes between cubical voxel cells and the input polyhedral (Kaufman and Shimony 1987) It is important to note that voxelization should be performed at best-fit bounding box of the element of interest to capture the highest data resolution with computational efficiency.

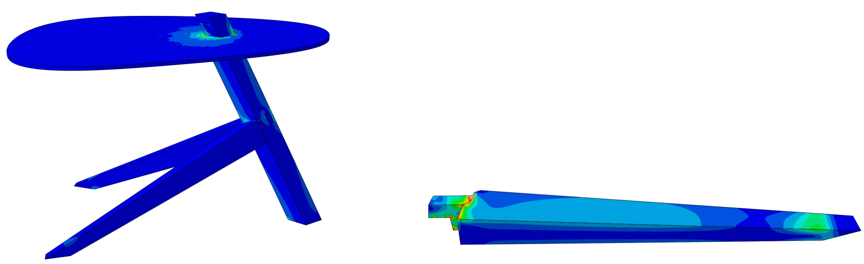

Figure 5. Finite element solid contact analysis results. Left: A visualization of normalized von Mises stress of the table under self-weight. Right: A visualization of normalize von Mises stress of a table leg.

Finally, for the material design process, von Mises stress information was normalised into the unit range. With this data attributes, we interpolated material composition such as nvm of 0.0 maps onto 100% elastomer material, 1.0 maps onto 100% thermoset material while nvm = 0.5 represents a ratio or 1:1. When the von Mises data distribution is too skewed or noisy, we use statistical methods to equalise the data. In addition, we extracted principle stress streamlines and assigned the thermoset material, that is analogous to fibre reinforcement or grain orientation, while the thickness of the streamlines reflects the stress values. In this particular instance, the streamlines were carefully designed with the criterion of both aesthetics and structure.

3.3. DESIGNING FOR FITTING

Similar to the design of microstructure of each table leg to enhance material stiffness, it is possible to modify the material layout in order to enhance fitting of existing applications (figure 6). Adopting the shrink-fitting principle of interlocking wood joints, the ends of the table legs which interface with the middle member are designed by juxtaposing a flexible compliant material (elastomers, Tango) within a stiffer outer shell (thermoset, Vero).

Figure 6. Photograph of a joint detail. A flexible compliant material is encased within a stiffer outer shell to improve fitting. (photograph by Jansen Teo photography).

Such a material composition allows the compression of the ‘male’ segment of the joint to facilitate the insertion into the middle member. Once interconnected, the uncompressed flexible material returns to its original state, locking the joint in place through contact pressure and friction force that acts locally on the interconnected surfaces of the joints. This also increases the pull-out force of the inserted joint, making it difficult to disassemble even if a force opposite to its assembly direction were to be exerted. Nonetheless, as the current design involves the arbitrary placement of the region of more compliant material within the stiffer outer shell, it is to be noted that further studies will be done to predict the behaviour of designed FGMs in the context of fitting applications.

4. Conclusion

The paper presents an approach to future Interlocking detail design based on the principles of designing Functionally Graded Materials (FGM). Our design case study of a furniture suggests a possibility of removing mechanical fasteners and adhesives from joint details by designing material stiffness, fitting, and geometry.Although current Multi-material additive manufacturing technology, due to its material selection and scale, is used for prototyping and not immediately deployable for buildings, developing design approaches with FGM could significantly impact the future architectural and structural design. To this end, we have designed and built a pavilion to demonstrate its applicability in architecture, which will be presented in our subsequent publications.

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References

Robert McNeel & Associates, ©: 2015, "Rhinoceros, Version 5.0" . Available from <https://www.rhino3d.com/> (accessed Feb 2017).

Autodesk, ©: 2016, "Monolith" . Available from <http://www.monolith.zone>.

Cao, Z. and Cardew-Hall, M.: 2006, Interference-fit riveting technique in fiber composite laminates, *Aerospace Science and Technology*, **10**(4), 327-330.

Chakherlou, T.N., Mirzajanzadeh, M. and Vogwell, J.: 2009, Experimental and numerical investigations into the effect of an interference fit on the fatigue life of double shear lap joints, *Engineering Failure Analysis*, **16**(7), 2066-2080.

Cutkosky, M.R. and Kim, S.: 2009, Design and fabrication of multi-material structures for bioinspired robots, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **367**(1894), 1799-1813.

Djumas, L., Molotnikov, A., Simon, G.P. and Estrin, Y.: 2016, Enhanced Mechanical Performance of Bio-Inspired Hybrid Structures Utilising Topological Interlocking Geometry, *Scientific Reports*, **6**(January), 26706.

Erman, E.: 2002, Demountable Timber Joints for Timber Construction Systems, *Architectural Science Review*, **45**(2), 133-143.

Ferreira, A.D.B.L., Novoa, P.R.O. and Marques, A.T.: 2016, Multifunctional Material Systems : A state-of-the-art review, *Composite Structures*, **151**, 3-35.

Ge, Q., Sakhaei, A.H., Lee, H., Dunn, C.K., Fang, N.X. and Dunn, M.L.: 2016, Multimaterial 4D Printing with Tailorable Shape Memory Polymers, *Scientific Reports*, **6**(April), 31110.

Guttag, M. and Boyce, M.C.: 2015, Locally and Dynamically Controllable Surface Topography Through the Use of Particle-Enhanced Soft Composites, *Advanced Functional Materials*, **25**, 3641-3647.

Hedia, H.S. and Nemat-Alla, M.: 2004, Design optimization of functionally graded dental implant, *Bio-Medical Materials and Engineering*, **14**(2), 133-143.

Jackson, T.R., Cho, W., Patrikalakis, N.M. and Sachs, E.M.: 2002, Memory Analysis of Solid Model Representations for Heterogeneous Objects, *Journal of Computing and Information Science in Engineering*, **2**(1), 1-10.

Kaijima, S., Xuereb Conti, Z. and Dunn, M.L.: 2016, A Design Oriented Workflow to Prototype Functionally Graded Designs based on Solid Finite Element Analysis, *International Association for Shell and Spatial Structures (IASS)*.

Kaufman, A. and Shimony, E.: 1987, 3D scan-conversion algorithms for voxel-based graphics, *Proceedings of the 1986 workshop on Interactive 3D graphics - SI3D*, 45-75.

Lee, S.W. and Lee, D.G.: 2005, Composite hybrid valve lifter for automotive engines, *Composite Structures*, **71**(1), 26-33.

Lee, S.W. and Lee, D.G.: 2007, Torque transmission capability of composite-metal interference fit joints, *Composite Structures*, **78**(4), 584-595.

Mahamood, R.M., Akinlabi, E.T., Shukla, M. and Pityana, S.: 2012, Functionally Graded Material : An Overview, *World Congress on Engineering*, **3**, 2-6.

Messler, R.W.: 1995, The challenges for joining to keep pace with advancing materials and designs, *Materials and Design*, **16**(5), 261-269.

Messler, R.W.: 2000, Trends in key joining technologies for the twenty-first century, *Assembly Automation*, **20**(2), 118-128.

OBJET, : 2016, "Connex multi-material 3D printing system, Stratasys" . Available from <http: //www.stratasys.com/> (accessed Feb 2017).

Oxman, N., Tsai, E. and Firstenberg, M.: 2011, Digital Anisotropy, *Journal of Virtual and Physical Prototyping (VPP)*, **4**(7), 261-274.

Ren, H.S., Liu, D., Tang, H.B., Tian, X.J., Zhu, Y.Y. and Wang, H.M.: 2014, Microstructure and mechanical properties of a graded structural material, *Materials Science and Engineering A*, **611**, 362-369.

Sobczak, J.J. and Drenchev, L.: 2013, Metallic Functionally Graded Materials: A Specific Class of Advanced Composites, *Journal of Materials Science and Technology*, **29**(4), 297-316.

Suresh, S.: 2001, Graded Materials for Resistance to Contact Deformation and Damage, *Science*, **292**, 2447-2451.

Dassault Systèmes, : 2016, "ABAQUS Version 6" . Available from <https://www.3ds.com/pr oducts-services/simulia/> (accessed Feb 2017).

Udupa, G., Rao, S.S. and Gangadharan, K.: 2014, Functionally Graded Composite Materials: An Overview, *Procedia Materials Science*, **5**, 1291-1299.

Wang, Y. and Lee, S.H.: 2014, Design and analysis on interference fit in the hardwood dowel-glued joint by finite element method, *Procedia Engineering*, **79**(1st ICM), 166-172.

Watanabe, R., Nishida, T. and Hirai, T.: 2003, Present status of research on design and processing of functionally graded materials, *Metals and Materials International*, **9**, 513-519.

Wu, X.L., Jiang, P., Chen, L., Zhang, J.F., Yuan, F.P. and Zhu, Y.T.: 2014, Synergetic Strengthening by Gradient Structure, *Materials Research Letters*, **3831**(July 2014), 1-7.