Mixed Matters: The Problems of Designing with Multi-materials

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Introduction

Background

In a recent TED article about the future of additive manufacturing, the things that could be 3D-printed soon would include houses, rocket components, meat and leather, virtually any food, liquid metal parts and high fashion items among others (TED Blog 2013). Even more strikingly, the incorporation of a 3D-printed moon habitat illustrated the range of applications that this technology can have on different scales. In aerospace, planning towards a widespread use of additive manufacturing outside of earth in the near future has led to the first 3D-printer being sent out to the International Space Station as part of a research project that will test the viability of the technology under conditions of microgravity. In parallel, the European Space Agency launched in 2013 a program termed "Addictive Manufacturing Aiming towards Zero Waste and Efficient Production of High-Tech Metal Products", under the auspices of which investigations are made towards printing the structure of a satellite as a singular element, which is something that "would save 50 percent of the costs – [that equates to] millions of euros" (RT 2013).

Apart from eschewing a series of mismatches that occur when assembling materials using conventional techniques (such as welding, bolting etc.) and as "the periodic table gives us around 60 commercial metal elements" (ESA 2014), there is the potential in place for drawing out further benefits from additive manufacturing by expanding the metallic material palette used in the satellite's 3D printed structure. According to ESA (2014), "in the world of materials it's the mixing of […] different chemical elements that is vital […]: we hardly use pure metals but we do use compounds, alloys and composites". Effectively, material admixture can inflict further reductions in the weight and costs of components. As a result, investigations in multi-material manufacturing in which "the actual number of combinations and ratios of mixing elements is infinite" (Ibid.) is already underway, while in fields such as material science it is now possible to use laser deposition (LD) in order "to fabricate multifunctional metal alloys that have a strategically graded composition to alter their mechanical and physical properties" (Hofmann et al., 2014). A demonstration of the benefits of using radially graded alloys can be found in "low-temperature spacecraft panels [where] carbon fiber/aluminum foam composites are widely used […] due to their high strength and stiffness, coupled with low density" (Ibid.). To be attached on other structures the composites need to be bolted through a threaded hole in the panel. Due to the extremely high temperature fluctuations occurring during flight, the Coefficient of Thermal Expansion (CTE) of the carbon fibre panel is different to the one of the metal bolts, which results in the two parts becoming detached from one another. Using a 3D printed bolt, however, that consists of a steel interior that gradually converts into Invar36 that has the same CTE as the carbon fibre panel, ingeniously resolves the mismatch between the two and allows for an 11% increase in the pull-out load on the panel.

Functionally Graded Materials

The idea of solid materials that vary their consistency and mechanical properties across their volume was already envisaged by Japanese scientists as far back as the 1970s and effectively realised in the 1980s. Termed functionally graded materials (FGM) they initially consisted of metals gradually fusing into ceramics within one continuous volume with no disruptions. Forty years later, research initiatives are beginning to indicate that the transfer of the use of graded materials from aerospace and material science to the building industry can have a very large impact in terms of cost, material and energy savings (Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2011). The same source, also suggests that "the important thing is that the building trade should be able to make practical use of ideas resulting from research into fundamentals, as well as methods, materials and advanced technology current in the industry".

In architecture and design, that are often notoriously slow to keep up with technological developments, initial research in the field of multi-material design is only beginning to become evident, albeit in a dispersed manner. According to Oxman (2010), "the mechanical response of materials designed and engineered with spatial gradients in composition and structure appears to be of considerable significance in all sub-disciplines of design – from product design, to medical devices, to buildings as well as technologies to fabricate and construct them".

Objective of Designing with Material Gradients

In light of these developments, the aim of the paper is to present a new procedure for designing with material gradients in an attempt to keep up with this foreseeable development in construction. What will be presented is the redesign, using multi-materials, of a conventional glazing-to-metallic frame connection, which is one of the points that cladding systems fail as a result of various underlying causes (Layzell 1997). A brief mention of the available digital design software that can incorporate material information is made initially, from which an appropriate tool is selected. The main parameters that are set in the tool are then analysed and discussed and a critique of the design outcome presented. As aforementioned briefly, the area of designing with graded information is to a large extent unexplored; the paper is therefore structured around (in this instance five) problems that one initially encounters when designing with FGM.

Scope Definition

Although already heralded as having the potential to enable radical changes in architecture (Wiscombe 2012; Oxman 2012), the research that is being made on FGM use in design also is to a large extent 'one-dimensional'. In a recent article Oxman (2012) suggests that "many qualities –such as improvements in strength, weight, material usage and functionality- could be obtained by the development and application of functionally graded materials at the product and architectural scales". Described in the article are suggestive applications of material grading in the form of variable porosity concrete samples, as well as "variable-density fabrication" with silicone and ABS plastics. In this case, the term functionally graded is confined to "spatially varying composition or microstructure" of a singular material, the porosity and density of which are made to change according to structural loading criteria.

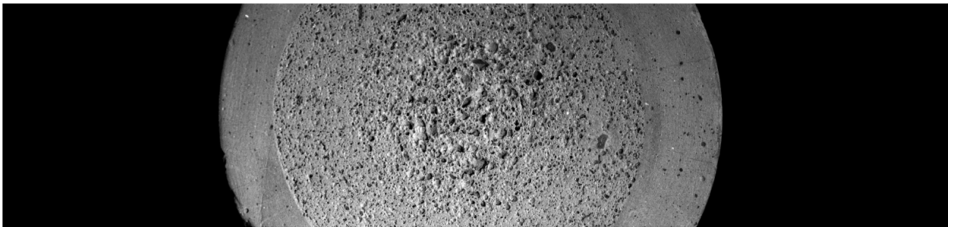

Fig. 1
Functionally Graded Printed Concrete, MIT Media Lab (Oxman and Keating, 2010-2012).

What this paper argues, however, is for a research that is more close to the original definition of FGM that "integrate a variety of dissimilar materials and properties" (Shiota & Miyamoto 1997). Design research would therefore become relevant and appropriate to the original purpose of the materials, as well as to current and future technological developments, if it was concentrated on design procedures for dissimilar material attachments rather than differentiation within the volume of a single material.

Fig. 2

FGM sample of ceramic (zirconia) on the left fusing into stainless steel on the right (Shiota and Miyamoto, 1997).

The Problems of Designing with Multimaterials

Problem 01- Inaccessible Information

When one is looking into the application of FGM in design, one of the initial problems is the lack of available data in regards to other precedents that can directly inform the design process. Information exists in a format that is addressed to specialised audiences and typically consists of scientific terminology that is to a very large degree incomprehensible and therefore inaccessible by architects. On the other hand, one can find publications in fields that are peripheral to architecture such as material science where there is a substantial amount of research but of a technical nature. At the same time the vast majority of this research is of an analytical scope, focusing mainly on the properties of FGM, the methods that they can be manufactured with, as well as how the different methods can affect their morphological, bonding and density characteristics (Yu et al. 2007; El-Hadad et al. 2010; Watanabe et al. 2009; Mahboob et al. 2008). As opposed to already established research areas such as the broader field of generative design for which there already exists a substantial literature, the nascent area of multimaterial design is only beginning to come into existence through a limited number of scattered design researches that vary greatly in their focus. In addition, there is lack of a comprehensive design theory or criteria through which it would be possible to critique and evaluate any relevant design projects.

Problem 02- Design Software Limitations

At present, material information and distribution have not yet made their way into the design process and as a result "most digital design packages employ a surface modeling paradigm where a solid object is that which is enclosed by a set of boundaries (known as boundary representations or "B-rep" for short)" (Michalatos and Payne 2013). According to Knoppers et al. (2005) and Oxman (2011), there is a limited number of packages within which material information can be assigned. In addition to the custom software devised by Knoppers et al. (2005) termed InnerspaceTM, these are voxel editing, finite elements, particle systems and vague discrete modelling software.

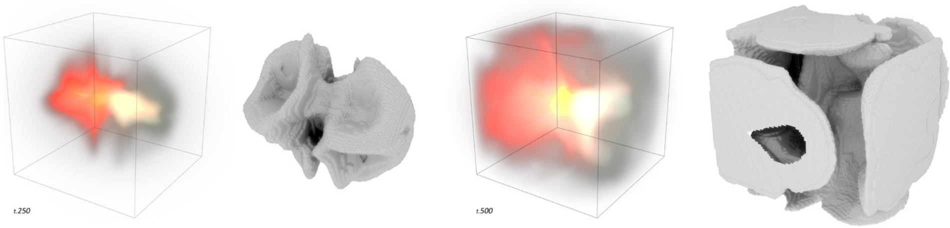

Fig. 3

Two different timeframes at 250 and 500 seconds of a voxel-based fluid simulation. On the left of each frame is the fused fluid system and on the right its mesh representation.

Having analysed these, the paper argues that apart from particle systems none of the above software take into account material behaviour which, when designing with materials being of equal importance to form, is of central value to the design process. More specifically, multi-material design is a process mainly concerned with the assigning of gradients between two or more dissimilar materials, as well as the extents of these. Being unable to attribute gradients based on criteria other than aesthetics, a designer ought to use simulations in order to allow for the gradients to be computationally calculated based on the physical properties of the substances to be fused. According to Longo and Zakhama (2013) "when the object of reality knowledge is based on, i.e. the first object (or archetype) is characterized by its opacity (in the case of science) or rather (again) is lacking (in the case of production), [the] knowing subject is in a position to use the model as a substitute for the first object, establishing it as second object". Here in essence, particle elements can do exactly that, which is the outputting of a computationally calculated material distribution space as a substitute for that which for the designer is opaque in terms of his/her potential to assign (or design) it. Particle system elements are by virtue of their computational structure made to simulate natural phenomena and effectively the behaviour of materials in their malleable state. They have therefore been used to simulate the graded fusion of materials in the glazing to frame connection presented.

In addition, according to Kieback et al. (2003) the main methods for manufacturing FGM can be divided in the larger categories of powder metallurgy and melt processing, which are both processes that as it will be illustrated can be simulated in a relatively straightforward manner using particle system elements. In fact, Realflow (RF) which is the specific software used in the design exercises, "consists on a complete set of simulation engines that cooperate to solve complex scene with multiple interactions among elements of different nature. RF computes object dynamics, fluids, particles, soft bodies [...] allowing as we said, the interaction of these elements" (Vučković 2009). The computation of fluids and particles in this case can be directly related to melt processing and powder metallurgy respectively.

Material Simulation- Definition of Parameters

When using particle systems there are two main parameters that affect the way material is going to be structured in space. Firstly, since the materials are of particulate or liquid type, the form of the mould that they are going to be contained or poured into is a main design aspect to be considered. Secondly, the forces or agency that affects the simulation also need to be placed strategically as there needs to be a "flow of energy rushing through the system" (DeLanda 1995) for materials to find an arrangement in space.

Mould Characteristics

In the case of the mould, the main design concern has been in terms of the formal characteristics that would allow for a more effective transfer of loads between glazing and structural frame, while at the same time attempting to reduce the overall amount of material in the connection. It was hence deemed necessary to look into examples where graded connections achieve this load transfer in a successful manner. According to Shiota and Miyamoto (1997) "natural materials found in living organisms are composed of graded or nonuniform structures and textures". In fact, the vast majority of connections in nature are graded (Rawlings 2002) and have resulted "from a long 'trial-and-error' process likely driven by evolutionary selective pressures" (Studart 2013). Places like the enthesis which is the point where muscles attach to bone utilize a range of ingenuous "mechanisms for overcoming the mechanical mismatch" (Thomopoulos 2011) between the two materials and in order to minimize the developed radial stresses throughout the connection (Studart 2013). A very large amount of literature has covered how this load dissipation is achieved, but overall these mechanisms operate on four main levels that are namely organ, tissue, fibre and micro-scale.

Graded Materials in Nature- Enthesis

The main aim therefore for configuring the materials at their point of fusion has been to borrow from these naturally occurring examples and towards informing some of the parameters in the simulation. At the level of the organ, one of the main techniques is the multiple attachment sites that eliminate any isolated connections between muscle and bone. According to Benjamin et al. (2006) "…most tendons and ligaments do not attach to the skeleton in an isolated manner. The enthesis of one often blends with that of another, so that many bony attachment sites overlap and this adds to the stability of the anchorage". In addition, what is proposed is that "what may appear to be discrete muscles are mechanically linked to each other by fascia that establish important lines of force transmission" (Ibid.). Another mechanism employed in the connection on a tissue level, is "the complex interdigitation of the layer of calcified fibrocartilage with the adjacent bone that secures attachment" (Ibid.). This junction point is effectively scalloped to "increase the bonding between the tissues"

(Ibid.). Lastly, on a formal level again, "the degree of the stress singularity […] depends on the angle of attachment; a shallow angle of attachment ameliorates [this…] singularity" (Thomopoulos 2011).

Simulation Agency

In the case of the affecting agency, the type and hierarchy of attraction daemons utilized in the simulation stemmed from existing techniques for FGM manufacturing such as centrifugal casting. According to Watanabe and Sato (2011) graded compositions are either of continuous or stepwise structure with the aforementioned powder metallurgy producing the former and the casting method generating continuous gradations. In terms of the casting, this consists of a preheated spinning mould containing particles of one material and into which a molten metal is poured. The centrifugal forces acting on the mould during processing, as well as the different densities and viscosities among other parameters, force the two substances at the two opposite ends of the mould with a gradient composition forming between them.

Resemblance of Digitally Simulated to Manufactured Multimaterials

In order to initially test out this physical principle in a digital environment, a simulation was set out using in this instance copper and aluminium. Their density and viscosity was attributed at 7,898 kg/m^3 density and 0.0312 m^2·s^{-1} kinematic viscosity for copper and 2,375 kg/m^3 and 0.01379 m^2·s^{-1} for aluminium. A vortex daemon was placed at the centre and the materials were released into a cylindrical mould with a time lag between the first and second pouring. Remarkably, and having gone into a formation that was changing periodically over specific intervals, the two substances eventually found their way towards either end of the container while at the same time being fused in the middle in a gradient manner.

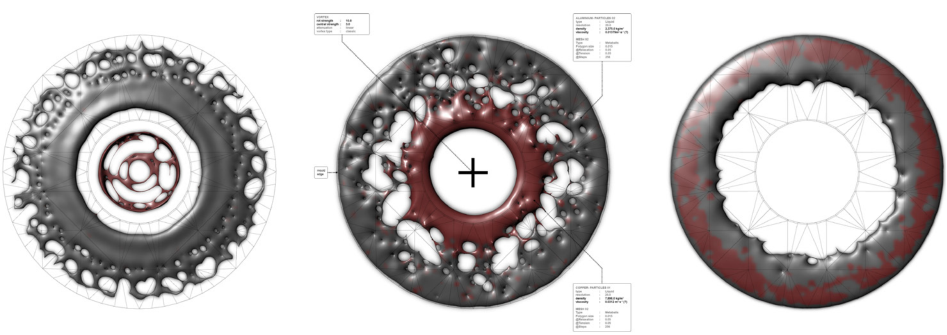

Fig. 4

The different timeframes at 13, 25 and 80 seconds of the copper (red) and aluminium (grey) fusion simulation under a centrifugal force.

Problem 03- Gradient Extent of Digitally Fused Materials

In this instance and although the formation of an FGM was achieved digitally, a further problem posed is the extent of the gradient at the area that the two materials blend. In order for the particle based output of the simulation to be visually discernible and in some cases 'renderable', a polygon mesh has to be generated that essentially is "a three dimensional representation of the outmost particles of one or more emitters. The mesh engine puts a sort of skin over these particles to visualize the fluid's volume" (NL Team 2010). In order for gradient materials to be mapped on this mesh, "per-vertex data is generated [and…] stored as a color set [that…] can be visualized by making it the current color set of the mesh" (Autodesk Maya 2014), with the overall visualization of the total data effectively giving the impression of a gradient. The ways this gradient is calculated by default, however, is through a built-in algorithm within the program that operates independently to any physical reality. Physically, the densities and other compositional characteristics of the individual materials to be fused affect the gradient extent in terms of length and area covered, as well as in terms of the potential micro-dispersal of one substance into another. In this regard, further research and customization of the tool and software is required for the gradients to be attributed accurately and subject to physical material parameters.

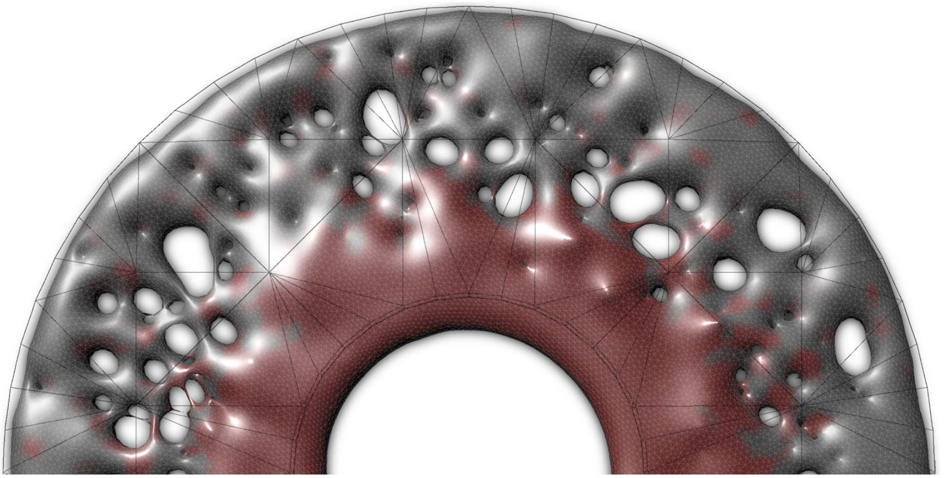

Fig. 5
Detail of the particle mesh showing the gradient extent between copper and aluminium.

Problem 04- Limited Micro-level Material Structuring Capabilities of Particle Systems

In addition, according to research by El-Hadad et al. (2010), it was found that "the centrifugal casting processing temperature in some reported studies showed a remarkable effect on the Al_3Ti particles distribution in the fabricated Al-Al3Ti FGM […] The processing temperature […] showed a strong influence not only on the Al_3Ti particles shape but also on the distribution of Al_3Ti particles size and volume fraction". This effectively means that when examining the material output from the casting process at scales of 0.05mm and above, one should be able to discern firstly the particles of the dispersed material (Al_3Ti in this case) forming platelets and secondly that the shape of these should vary according to temperature fluctuations as well as the centrifugal force intensity. Watanabe and Sato (2011) state that "it has also been found that the particle size gradient in the FGM becomes steeper with increasing the G number or with decreasing the mean volume fraction of particles".

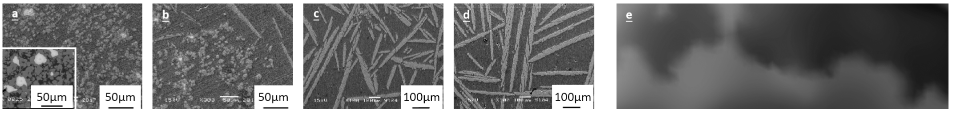

Fig. 6

"Scanning Electron Microscopy (SEM) micrographs" of FGM processed at 1150oC (a), 1250oC (b), 1350oC (c), 1450oC (d), showing differentiation of platelets according to the processing temperature. A magnified detail (e) of the resulting FGM from the material simulation shows no platelet formation.

Although there would be a microscope needed in order to discern these formations of the physical material, in the digital environment there is the ability of large magnitudes of zooming into specific parts to examine whether this clustering is the case as well. Having examined the polygon mesh that was generated in the simulation, no visible platelets were formed, which only illustrates the limited micro level material structuring capabilities of the particle system elements. Similarly to the aforementioned gradient extent, customization of the software would be required, with material formation patterns from existing scientific research informing the programming of the behaviour of the particles in order to achieve results that are more accurate to physical material reality.

Design

The Problem with Existing Cladding Interfaces

When considering the advantages that multi-materials can have when used in the design of architectural elements, an initial application of the aforementioned design methodology can be in conventional curtain-walls that typically consist of 'the components of cladding most likely to fail according to the qualitative survey (CWCT 1997c)' (Layzell 1997). Additionally, according to Kazmierczak (2010), "interactions between building facades and structure are notoriously disregarded in the design phase […]

[with this oblivion] manifested in field failures, ranging from persistent leaks of inadequately designed seals to rare but spectacular collapses caused by inadequate joinery". Furthermore, "gaps of oversight and coordination in the established project delivery routines" (Ibid.) in facade systems that are "designed and built by separate organizations" are usually a result of processes "of chaos and conflict" (Wiscombe 2012). In an imminent ensuing scenario of printed construction in which fused materials serving different functions are distributed and embedded within a surrounding material matrix and where the redundancy in conflicting trades and tectonic systems is becoming eliminated, there is a valid point in already performing design studies that are based on these material and construction advances.

Materials Utilised in the Simulation

In terms of material selection, the intent was to initially use aluminium and glass that are typically used in curtain walls; however, it has not been possible to identify any existing research that demonstrates the coexistence of these two materials in an FGM. There are, however, studies by Yu et al. (2007) of sintered glass-alumina FGM, as well as by Mahboob et al. (2008) of aluminium-alumina nanocomposite materials that were produced with mechanical alloying. It would be possible therefore, as existing research shows, to use a ceramic (alumina in this case) bridge material in order to bind aluminium and glass on its two ends and in order to generate a continuous transition from one phase into the other. Indicatively, in its liquid state glass has an approximate density of 2,500 kg/m^3 (Gaskell 2012) and kinematic viscosity of 1 m^2·s^{-1} (NL Team 2010), alumina a density of 2,830 kg/m^3 (Jahn and Madden 2008) and kinematic viscosity of 0.0000019 m^2·s^{-1} and lastly for aluminium the same values as above were input.

Mould Form and Design Output

With these parameters in mind, the next part of the set-out was to design the mould that the materials would be simulated within. This was designed as a continuous enclosed volume and with the same proportions and dimensions as a typical curtain wall part.

From the aforementioned formal mechanisms employed in the enthesis and at the place of the attachment of the inner glazing to the supporting frame, the connections were designed with the principles of multiple attachment sites and use of shallow linkage angles between the two parts.

The simulation was ran with the alumina initially placed in the centre and aluminium and molten glass on either ends of the container. The material formation reached a balance after approximately ten seconds and eventually terminated at twelve.

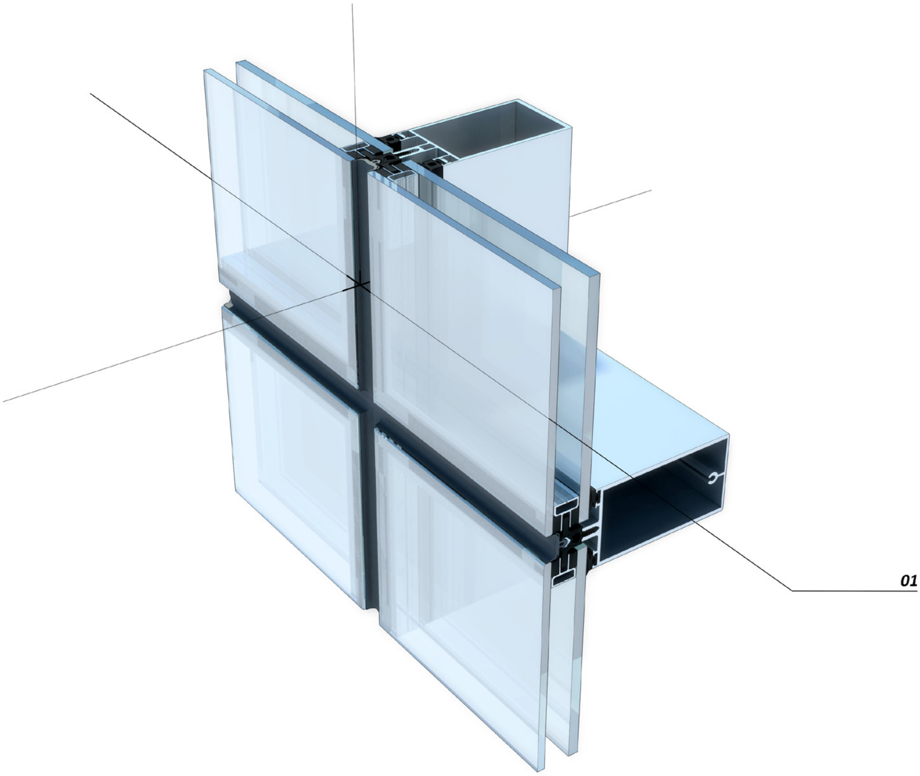

Fig. 7
A typical curtain wall detail showing the part that was redesigned using multimaterials (01).

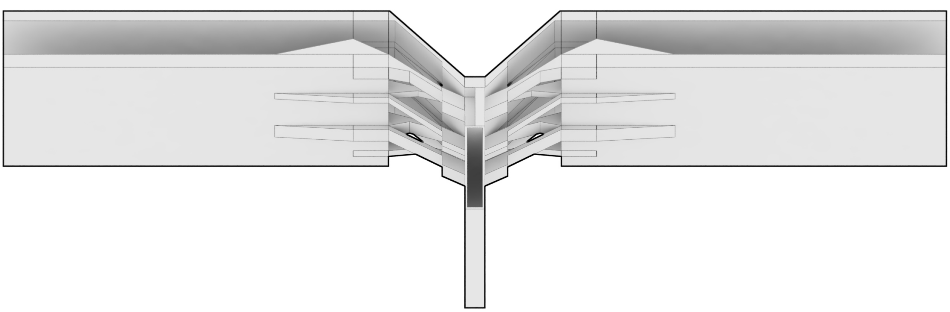

Fig. 8.
The mould used in the material simulation.

Problem 05- Representation of Multimaterials

A fifth problem when designing with FGM is the fact that there is a limitation in the type of materials that can be visualised when rendering the overall mesh. Rendering parts that are solid can be easily attributed and mapped on the output mesh using the per-vertex data, however, when it comes to transparency rendering engines cannot attribute it within continuous volumes consisting of more than one material. The alpha channel of glass was in this case used in a raster graphics-editing program to remove a default solid material used in the place of glass and substitute it with a transparent material.

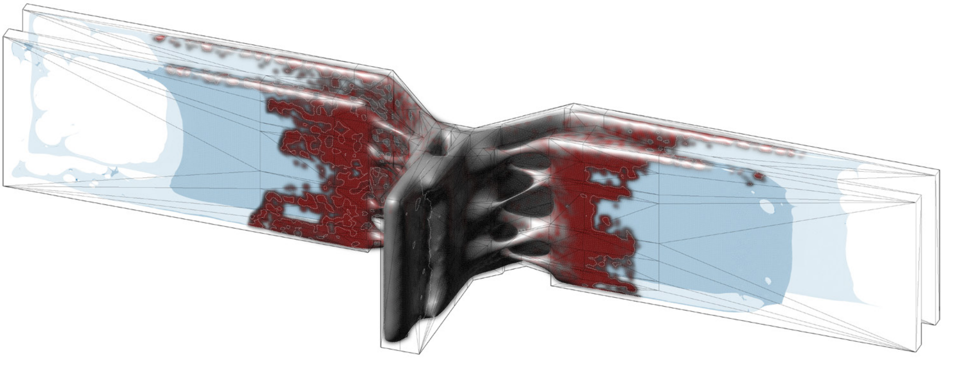

Fig. 9

Aluminium (grey part) fuses into alumina (red) that gradually merges into glass (blue area) in the resulting multimaterial skin to structure connection.

Conclusion

Regarding the output design, there were a few characteristics including the aforementioned attachment angles, as well as the interdigitation of the materials at their point of fusion that were borrowed from the enthesis and applied successfully in the cladding detail. On that respect, however, this translation was operating mainly on a formal level without having control or a specific objective for the structuring of the material at smaller scales.

In the case of the enthesis, changes in collagen and mineral content enable the gradual morphing of the fibrous composition of muscle tissue into the mineralised one of bone. This gradation in material properties at the point of connection is a result of the different functions that muscle and bone have to perform. Similarly, the different functions of the parts forming the cladding system of a building, as well as the loads that act upon them have to be analysed further and more accurately. This will enable more concrete conclusions to be made in terms of the ways that the fused materials have to be micro-structured for a more effective dissipation of loads, in a manner similar to the enthesis.

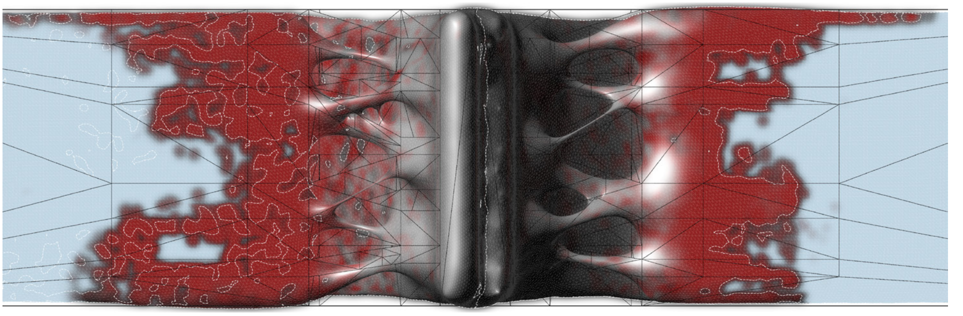

Fig. 10
Detail of the connection showing interdigitation and multiple attachment sites.

Lastly, further research has to be made in attributing with more precision the affecting agency in the simulation as informed by existing FGM manufacturing techniques. In this instance and although the forces acting upon the materials in the digital environment were the same as centrifugal casting forces, in order to achieve interdigitation, there were 'exclusive links' attributed within the simulation environment. This effectively meant that there was a force acting only on one material in isolation, which is something that would not occur physically, as gravitational, centrifugal or other forces always act on all materials placed within their field of influence. In this regard and although there is further scope in improving the parameters that are incorporated into the design studies, it is envisaged that in the imminent multi-material future material, energy and cost savings are going to be the new reality, while fields of gradients as opposed to sharp boundaries will be the ensuing design aesthetic.

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