Low-Cost Housing

Testing snap-fit joints in agricultural residue panels

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Within the field of digitally fabricated housing, the paper outlines a theoretical model for a housing system that combines complete off-site prefabrication with parametric assemblies. The paper then presents some insights on the application of snap-fit joints to the wall assemblies entirely fabricated using agricultural residue panels. Mechanical characterization of the material was performed through axial tension, compression and 4-point bending tests. Guidelines of plastics snap-fit design were applied to the joint design within the elastic limits of the material. Three different full scale wall typology prototypes were built using this jointing technique. The results show that while snap-fits can be a promising solution encouraging self-build in low-cost housing, the brittle nature of the specific agricultural residue panel material necessitates further joint enhancements.

Keywords: Digital fabrication, Low-cost housing, Agricultural residues, Structural testing

RESEARCH MOTIVATION AND BACKGROUND

In a world with diminishing resources and changing climatic conditions, the concepts of sustainability are becoming a critical broad background to research and practice. The world population is increasing at a rate that is shockingly rapid. The livelihood and safe housing environments are becoming increasingly difficult to obtain in developing countries. Motivated by this rising demand for affordable housing especially in poor and developing countries, the authors had previously performed an investigation that examined built prototypes of digitally fabricated houses within twenty years (1995 - 2015). It was an attempt to understand the limitations and potentials of using digital fabrication in the affordable housing sector in developing countries (Elsayed & Fioravanti, 2015).

Among the most important limitations was the almost exclusive usage of plywood and timber in general as the core building material for this approach of housing as it is easily machined using relatively affordable digital fabrication tools. This becomes an evident limitation when working in countries that have no tradition of building construction using timber, or mainly depend on imported timber. On the potentials side though, digital fabrica-
tion still promises to provide a process that is efficient and rapid while maintaining the possibility of mass-customization through coupling fabrication tools with parametric design.

Moreover, from an environmental point of view, many developing countries with long tradition of agricultural activities face a yearly challenge in the harvest season. The process of harvest produces large amounts of residue that must be disposed of. Unfortunately, the current practice is largely burning these residues forming huge black clouds of smoke above surrounding villages and cities. The environmental impacts of such practice are utterly harmful causing multiple lung diseases, needless to mention other negative effects. There has been on-going research exploring the use of condensed, treated rice straw as a building block (Mansour, et al., 2007, Akmal, et al., 2011). Few researchers started exploring potential use of rice or wheat straw residues in flat sheets. This particular application is of great potential to the field of digital fabrication in which the authors are involved.

**PRECEDENTS IN DIGITALLY FABRICATED HOUSING**

Wikihouse (1); Instant House (Botha and Sass, 2006); Shotgun House (2); ECOnnect Haiti emergency shelter (Stoutjesdijk, 2013) are all examples that demonstrate the potentials of using digital fabrication coupled with Do-It-Yourself approach in housing construction where the end-user is seen as an active contributor to the assembly/construction process. These prototypes skillfully represented quick yet temporary responses to emergency housing situations however little attention was given to analytical structural aspects and long term living space requirements. For instance, the Instant Cabin and ECOnnect emergency shelter have an area that is less than 20 square meters with no wet spaces which is understandable in emergency situations but not for long term living.

From this starting point and with the aim of finding solutions to the pressuring problem of housing in developing countries, we explored alternative materials that can be utilized for housing construction while having minimal environmental impact. With the criteria of environmental and financial sustainability, low cost, simplicity of construction, customizability and ease of transport; the authors scanned the construction market for stock sheets made of compressed agricultural residues.

**AIM AND OBJECTIVES**

The paper attempts to address and understand the structural performance of agricultural residue based sheets in the construction process utilizing digital fabrication tools and snap fit joints. ECOboard (3) is a wheat straw resin-bonded fiber panel product produced by a Chinese company and introduced to the European market under the commercial name ECOboard. The commercial data sheet gives high mechanical resistance values which tend to be overestimated for marketing reasons. The data sheets also mention values related to moisture content, thermal performance and fire resistance. The author at this point is solely interested in verifying the mechanical material values to understand the possibility of using these panels as principal load bearing structural elements within wall, floor and ceiling assemblies designed with snap-fit and friction-fit joints with no adhesives or bolts. Within the scope of this paper, a set of 3 mechanical tests were performed as will be demonstrated. Three different wall typologies were built but due to time limitations, their structural testing is not shown within this paper.

**PROPOSITIONS OF A LOW-COST HOUSING SYSTEM**

Within these premises, the author proposes a housing system (Figure 1) that is mainly comprised of: Firstly, modular parametric wall, ceiling and floor assemblies. By parametric we intend going beyond being modularly and dimensionally fixed. The wall assembly overall internal and external dimensions can be changed based on layout design decisions of the client and the architect. Secondly, a factory built prefabricated core that contains wet spaces of bath-
room, kitchen and mechanical equipment with the aim of reducing on-site construction complexity.

There are certain time and budget benefits for combining these two systems together. The construction of a new site-built home in the US for instance, typically consists of 80% labour and 20% material cost (Larson, et al., 2004). While using modular panelised approach saves time for on-site construction, the utility services and mechanical system connections consume large amounts of time for onsite installation. Hence the housing system proposed by the authors promotes off-site fabrication for the more complex part of the housing system in search for cost savings associated with controlled environments that factories can offer. Better working conditions, automation of some tasks, fewer scheduling and weather-related problems, and simplified inspection processes are all seen to be strong players for the reduction of costs associated with on-site construction.

The parametric assemblies are meant to be built entirely of flat sheet material (agricultural residue panels) using snap-fit and friction fit joints. The constructive logic is based on stand-alone hollow cassettes that are assembled within themselves and to the neighbouring ones using snap-fit easy-to-assemble and disassemble joints (Figure 2). This choice was made to ease fabrication and encourage self-build by unskilled home owners.

CHARACTERIZING THE MATERIAL

The ability to define reliable mechanical values of the material to be used as safe design values is an indispensable step in dimensioning the cantilever snap-fit joints and structural elements of the modular system. The material comes in different flat panel thicknesses such as 9, 12, 15, 16, 18, 19 and 25 mm. The Modulus of Elasticity (MOE) and bending strength provided by the manufacturer for the 18mm thick standard panels were 3810 MPa and 38 MPa respectively. These values cannot be regarded as safe design values as they were taken from a commercial data sheet which generally tends to be over-estimated for marketing reasons. The reports received from the company did not mention which norm was followed for testing the mechanical properties. Hence, it was important to perform basic mechanical tests which can give a better indication of the material behavior of 18mm thick stock sheets.

The tests included: axial tension, axial compression and 4-point bending. The European norm EN789 (Timber structures - Test methods - Determination of mechanical properties of wood based panels) was used loosely as a general guideline for the test pieces’ preparation, loading arrangement and procedure. The norm was not fully met due to several limitations such as availability of specific testing machinery, relatively large test-piece dimensions required by the norm. The results of lab experimentation on the 18mm sheets shall be seen merely as indicative as the tests were only performed twice in different panel orientations while the norm states performing each test 4 times in a given panel orientation.

The material showed overall good resistance values, however, the obtained Modulus of Elasticity in bending was 2100 MPa which is 44% less than the commercial values provided by the manufacturers while the bending strength was found to be 14 MPa which is almost 60% lower than the commercial
value. The material showed elevated levels of resistance in pure compression (9.2 and 11.1 MPa for two tests) and lower resistance in pure tension (7.2 and 8.5 MPa for two test). It was observed that the material has a brittle behavior in tension (Figure 3). This can be largely attributed to the very fine fibres that the material is composed of.

In compression, it was observed that failure was consistent with natural wood failure modes. The first test piece failed with shearing while the second test piece failed with a combined mode consistent with crushing and splitting. The material showed consistent behaviour for the two test pieces with no observable difference between panel orientations. Given the artificial nature of the material being a composite with its characteristics depending primarily on the bonding material (resin) therefore, a coherent result was expected with no major deviations. These values
are considered very important inputs for the design of an efficient snap-fit and friction fit jointing system.

Figure 3
Failure of test piece under axial tension.

SNAP-FIT AND FRICTION-FIT JOINTS

Any Snap-fit joint consists mainly of one male part and one female part. The temporary bending of the cantilever part allows for the fit of the two pieces using the material elastic behaviour. After the joining operation, the two parts return to a stress-free state. (Robeller, et al., 2014).

Although snap-fits can be designed with many materials, the design manual developed by BASF (2007) and BAYER (2012) deal exclusively with different thermoplastics because of their high flexibility and their ability to be easily and inexpensively moulded into complex geometries. Within the scope of this research and with the aim of simplifying the process of fabrication, only straight cantilever joints will be used. Other more complex joints like “U” and “L” shape cantilever snaps with the presence of under-cuts necessitate the use of complex fabrication -such as subtractive multi axes robotic fabrication- which would significantly raise fabrication time, cost and complexity. Snap fits were studied previously by Robeller et al. (2014), using cross-laminated veneer lumber (LVL) as the base material in the context of shell structures. LVL material composition and stratification implies a certain behavior to local stresses that was simulated by Robeller et al. using Finite Element Analysis (FEA) tools and verified later by physical testing. It is therefore expected that with a material that has a different internal composition, bonding and overall mechanical performance; to have different response to stresses and thus different structural performance.

BASF (2007) design guide explains that snap-fit joint dimensioning can be approached in two different ways. Material first: were a material has been already chosen with known allowable strain and then dimensions are designed to fit it. Dimensions first: were primary dimensions are fixed and then a material research is performed to select an appropriate material that allows using those dimensions. In this case, a material selection has been already done, so the design activity becomes defining the proper dimensions for the joint. When designing a cantilever snap, it is not unusual for the designer to go through several iterations (changing length, thickness, deflection dimensions, etc.) to design a snap-fit with a lower allowable strain for a given material (BASF, 2007).

One of the usual approaches for snap-fit design is to start from a group of design approximations or assumptions. In the case in hand, we started from an initial rough geometry for both part and mating part (Figure 4). The cantilever beam length (l) is assumed to be 90 mm, and the height at base (hbase) to be 19 mm. A tapered cantilever was also used in order to minimize the uneven distribution of strains on the material. For all the calculations, it was assumed that the mating part of the snap-fit remains rigid while all the flexural stresses happen in the cantilever beam (BAYER, 2012). This assumption represents an additional precaution against material failure. The cantilever base connects to the wall using a root radius of 4 mm. While the guidelines propose a ratio of 0.6 between radius of fillet and height of beam (R/hbase), it however acknowledges that this would result in a large base at the cantilever connection with the supporting wall. It calls upon the designer to reach a compromise between a large radius to reduce stress concentration or a smaller radius to avoid residual stresses due to the creation of a thick section adja-
The initial assumptions used for the design of the snap-fit joint, taking into consideration milling machine limitations, required geometry and some best practice assumptions.

The entrance angle was assumed at $20^\circ$ while the retraction angle is kept at $90^\circ$ to ensure that the disassembly is not too easy under circumstantial pulling forces.

Various trials were performed to test the integrity of the cantilever beam arm. While keeping the cantilever base height at 19 mm, two different trials were made changing only the length ($l_{\text{min}}$) of the cantilever beam. One trial at a length of 90 mm, the second at a length of 76 mm. While the longer beam length allowed for easier deflection and accordingly easier assembly, it was easily broken under hand-applied force. The shorter beam however, showed better overall resistance given that sufficient tolerance is considered for the mating parts.

Given the accuracy with which the dimensioning calculations are made, fabrication tolerances also had a considerable effect on the overall performance of the cantilever beam. The fabricator was provided with a CAD file for the first joint trial in which 1 mm tolerance was designed to accommodate for the accumulated tolerance effect that might arise with the assembly of a big number of pieces. This tolerance also accounted for imperfections in material sheet thickness and any eventual expansion due to moisture or heat. However, on an individual scale, this tolerance was found to affect the overall integrity of the joint making it considerably loose. The subsequent fabrication trials were designed at zero toler-
ance while assumed a machining tolerance of 0.3 mm (set from CAM software) for the tab holes and this value proved satisfactory for the individual and accumulative tolerance requirements. Three wall typologies were modeled then fabricated using an open source CNC milling machine (Figure 6).

Figure 6
Three CNC milled wall typology full scale prototypes.

OBSERVATIONS AND CONCLUSIONS

While the process of assembly was smooth and quick in which the author by himself assembled the three wall typologies with very little help in less than an hour, some challenges were faced during assembly that require further enhancement and optimization. This section provides some insights on these issues and the prospective steps that might be taken to address them.

It can be concluded that this material with its characteristic fine fibers is not best suited for delicate joining. Although the joint was designed within the elastic limits of the material, some of the snap-fit cantilevers were broken during assembly, specifically 4 out of 58 cantilever arms which is around 7%. The brittle nature of the material was a very noticeable aspect during assembly. These failures might be attributed to local material weak zones or to applying high strains -beyond the material’s allowable strain- during assembly of more than one cantilever arm in the same time. However, it is evident that the dimensions of the snap fit cantilever in brittle materials is a critical issue that needs further analysis and design optimizations.

It was observed that the overall rigidity of the assemblies increase with the increase of number of components and their bi-directionality. For instance, the L wall was more rigid than the straight wall and the T wall was more rigid than the L wall and so on. This is quite logic as the contact surfaces between different components increase and thus increase the system’s global rigidity. The straight wall was more prone to skewing in the horizontal plane while the two other assemblies where much better on that front. This necessitates adding horizontal bracing profiles within the straight wall and between different assemblies.

The integrity of the edges in direct contact with snap-fit were prone to fiber crushing due to high friction during assembly. The bonding strength of the exposed edges in this material is questionable. It is critical to find good tolerance balance that would account for this edge weakness while not compromising the retaining force of the snap fit.

SIGNIFICANCE OF THE RESEARCH

Based on availability in local markets, the selection of wheat straw as the base material promised to address more than one issue concurrently; First, fits the available relatively cheap digital fabrication technologies available through Fablabs and hacker spaces. The standard equipment that are provided by these labs is considered a defining factor to the development of this housing technology as the intention is democratizing the process of construction by providing access to means of production and making it available for low-income populations. Second, adds economic value to materials that previously had little value. Third, lower the initial cost for the construction of the house if used in a structural manner. Fourth, minimize the environmental impact of abundant un-used agricultural residues.

OUTLOOK

The paper gave some insights to the design and fabrication of snap-fit joints in brittle materials through better understating of structural performance and assembly behaviour using agricultural residue panels.
The designed joint will be optimized and revisited in the light of this specific material behavior implying rethinking issues of tolerance, edge clearances and friction fitness.

On the contrary to snap fits, the half-lap joint insert which was used the L wall and T wall assemblies showed high resistance and strong fit during the construction of the prototype. This type of jointing can be further explored as a substitute to cantilever snap-fits in brittle materials. These enhancements or possible joint concept trials are part of the future work.

The wall assemblies -rather than only the stock material- are scheduled for structural testing but due to the busy time schedule of the testing laboratory it was not possible to finish them within the time frame for this paper. They will however be part of a subsequent publication.

The results of the structural testing are not intended to be seen as the ultimate result of the paper but as an initiator of a broader discussion within the architecture audience interested in architectural materials, sustainability and affordable housing about the viability of using this material and this jointing technique for low-cost construction.

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