Finite Element Analysis of Reinforced Structural Fibre-Glass and Recycled Plastic Blocks in Low-Cost Houses

Otieno, R. K., Mureithi, N., and Hussein Ahmed

Transport Department, Multimedia University of Kenya
Center for Biodiversity, National Museums of Kenya
Civil Engineer Enterprise Constructions, Kenya

Corresponding Author: Otieno, R. K

Abstract
Disposal of plastic wastes is a major global problem. One of the best solutions to the problem of disposal of plastic wastes is through recycling to produce other usable composite materials leading to improved environmental sustainability. It is important for developing nations to build capacity for plastic waste management to ensure clean environment. One of the areas for capacity building is in the construction industry. The industry is a major consumer of costly cement, sand and aggregate whose costs can be reduced by use of recycled plastics processed through melting and re-moulding into desired blocks and structural building materials. The main goal of this research is to help in attaining sustainability in development through recycling of plastic wastes for affordable housing. Research objectives were to design a low cost house made of recycled plastics and composite materials for building; to analyze mechanical behaviour of the building using finite element analysis in Simulia Abaqus and to propose measures to scale up production. Loading was by concentrated loads on truss and pressure on the roof and wall surfaces. Wind effects on the house were studied in Solid works flow simulation module. Results show that high strength fibre glass structures and the roofing sheet materials experienced high stresses. Stresses on recycled plastic blocks on walls were low.

Keywords: recycled plastics, finite element method, sustainability, low cost housing

INTRODUCTION
Capacity building in waste management is key to achieving sustainable development. One of the problems facing nations is how to effectively handle plastic wastes. Consumption of plastics has been on the increase with global per capita consumption ranging from 30kg in 2005 to 45kg in 2015 (Bernardo, Simões, & Pinto, 2016). Global production of plastic in 2014 alone hit three hundred and eleven million metric tonnes (Vegter, et al., 2014). In Middle East and Africa, per capita consumption of plastic increased from 10kg in 2005 to 16kg in 2015 (Vegter, et al., 2014). According to Ong’u ya, Aurah, Nabwire and Songok (2014) twenty four million plastic bags are consumed monthly in Kenya of which half has become part of solid waste. Plastics are a challenge in Kenya and more specifically, in Nairobi (Horvath, Mallinguh, & Fogarassy, 2018). This is because plastics pollute soil, block drainages and are not bio-degradable (Ong’u ya, Aurah, Nabwire, & Songok, 2014).

Problem facing efforts to reduce use of plastics has been related to the capacity of nations to manage their disposal and re-use or recycling. Efforts to abolish use of plastics in Kenya have also been have been thwarted by reluctance to change and black market (Horvath, Mallinguh, & Fogarassy, 2018). Even though there exist ban in plastics in countries in the East African region including Kenya and Rwanda, there is still a considerable quantity still being produced and used in the countries (Njuguna, 2018). Currently, the Nairobi dumpsite in Dandora is in residential area and is overwhelmed by massive dumping of plastics and other wastes (Ong’u ya, Aurah, Nabwire, & Songok, 2014; Elliott & Cook, 2018). This clearly indicates an urgent need to recycle the plastics and also build capacity to use them for sustainable development such as in achieving low-cost housing as one of the four big pillars of Kenya’s vision for sustainable economic development. The key question is do we have local or regional research on how the plastic wastes can be used to achieve dual objectives of affordable housing and sustainable environment? There is need to have research focusing on assessment feasibility of the recycled plastic housing.

to plastics problem through buildings. These research efforts contributed to efforts to recycle and need for affordable buildings and to conserve environment. The plastics that create environmental problems can open a new horizon in the building industry (Foster, 2013). The plastics can be engineered into composites; an innovative recycling to contribute to housing and sustainability (Foster, 2013). This can help reduce the cost of building by resorting to cost-effective production of plastic blocks and high strength fibre-glass (Ong’uya, Aurah, Nabwire, & Songok, 2014). It also helps to reduce weight of building especially for storey houses (McDonough, 2011). It is also an avenue for employment creation for the population; especially the youth.

This research focused on engineering aspects of broadening materials applications as a first step to capacity building in producing affording housing using recycled plastics. It examined engineering feasibility of recycled plastic housing by considering application of reinforced high-strength fibre-glass for structures and recycled plastic blocks for walls. Other aspects of capacity building would be studied during prototyping and up-scaling for production. This paper only focuses on finite element analysis of structures to simulate forces and stresses that would point to the need to proceed with actual production.

**LITERATURE REVIEW**

**Recycled Plastics in Buildings**

Research has focused on use of recycled plastics as building materials (Arulrajah, Yaghoubi, Wong, & Horpipulaksuk, 2017; Corinaldesi, Domnini, & Nardinocchi, 2015; Mansour & Ali, 2015). Considerable research has been conducted on plastic – concrete composites (Dehghan, Peterson, & Shvarzman, 2017; Gu & Ozbakkaloglu, 2016; Sharma & Bansal, 2016; Silva, De Brito, & Dhir, 2014). Gu and Ozbakkaloglu (2016) conducted a review of 84 studies on the application of recycled plastics in concrete to form aggregate plastic fiber-reinforced concrete.

They summarized the influence of properties and plastics recycling methods on properties of concrete. The review included the morphology of plastic-concrete composites was also reviewed (Gu & Ozbakkaloglu, 2016). Silva, De Brito and Dhir (2014) reviewed 236 research publications within 38 years up to 2014 to examine the factors affecting the properties of recycled aggregates formed from wastes. They classified the wastes based on composition and contaminants and analyzed data for concrete construction. The findings were intended to produce ways of measuring the quality of recycled plastic-concrete aggregates with predictable performance levels. Though incorporation of plastics in concrete prevents their direct contact with the environment, this method is not widespread plastic disposal technique. Sharma and Bansal (2016) presented a summary of some research on use of waste plastics in concrete. They also presented the effects of waste adding plastics on the mechanical and thermal characteristics of concrete. Dehghan, Peterson, & Shvarzman (2017) noted that adding fibers to concrete retain polymer and filler materials and are beneficial in achieving higher strengths. They examined effects of recycled fiber glass reinforced polymers on concrete. They found that the compressive strength did not improve when glass fibre reinforced polymer was added but splitting tensile strength was improved. Very little expansion was noted and there were pozzolanic reactions of the glass fibers.

Some research has also been conducted on plastering and insulation of buildings using recycled plastics (Corinaldesi, Domnini, & Nardinocchi, 2015; Schiavoni, Bianchi, & Asdrubali, 2016; Vojta, et al., 2017), Corinaldesi, Domnini and Nardinocchi (2015) studied environmentally-friendly plasters which are fully composed of waste particles. The study used plastic waste particles obtained from bottles. They found out that plasters with a lot of organic particles and lime can replace cement and that they had good functional characteristics and reasonable mechanical properties. Schiavoni, Bianchi and Asdrubali (2016) reviewed the main commercial building insulation materials with consideration for thermal, acoustic, reaction to fire and vapor resistance. They compared performance with that of unconventional insulation materials. They also evaluated thermal transmittance and dynamic thermal characteristics of walls with various materials. The findings were that recycled plastics performed well compared to other materials. Vojta, et al. (2017) examined composition of fire retardants in 137 samples of waste products to identify and characterize source of fire retardant. The analyzed contents included were poly-brominated diphenyl ethers and novel flame retardants. It was found out that there were differences in fire retardant contents across groups and that there were differences in fire retardants between recycled and non-recycled plastics. For recycled plastics there were low levels of many fire retardants.

Other researchers have focused on plastic building panels for low cost housing (Vailati & Monti, 2016). The research propose plastic and fibre glass composite panels on steel structures which are joined together to form house units. The commonly used recycled plastics include recycled polypropylene (de Macedo, dos Santos, Balanco, Christoforo, & Lahr, 2015; El-Betar, 2017), polycarbonates (Moretti, Zinzi, & Belloni, 2014; Wright, et al., 2018) and high density polyethylene (Moussa, et al., 2018; Maroy, Van Linden, De Vogelaere, Van Den Bossche, & Steeman, 2017), among others. Research has also been done on applications of high-strength structural
fibre glass (Landesmann, Seruti, & Batista, 2015; Rizvi & Sharma, 2015). It has been found that composites of fibre glass perform well in structural applications especially in corrosive environment (Wright, et al., 2018).

Methods of stress and strain analysis of structures and wall components of buildings as well as sheets have been done using various approaches such as experimental methods (Hu, Li, Chen, Zhao, & Yang, 2017; Shen, Yang, Jiao, Cui, & Zhang, 2017), simulation approaches which include finite element analysis (Naya, Molina-Aldareguía, Lopes, González, & L.Lorca, 2017; Zeng, Guo, Li, & Chen, 2018). The next section reviews research on plastics in buildings using finite element analysis.

Finite Element Analysis of Plastic Materials
Numerical modelling of buildings with conventional materials has been researched for a long time (Dutil, et al., 2014; Gams, Kwiecień, Korele, Rousakis, & Viskovic, 2017; Nguyen, Tran, Ngo, Tran, & Mendis, 2014). Research in numerical modeling of plastics and modern composite materials is growing, with a greater focus on finite element methods (Nguyen, Tran, Ngo, Tran, & Mendis, 2014). Khelifa, Auchet, Méausoone and Celzard (2015) carried out finite element analysis of flexural strength of timber and found out that evolution of damage of the beams was correctly predicted.

Plastics have been found to have strains which are much larger those in metals with ultimate tensile strains of plastics can be more than 30% (Cogger, 2009). It is known that finite element codes were normally designed to work within the ranges of total strain within 2-5% with kernels and displacements algorithms not usually meant for very big displacements. According to Cogger (2009) the elements and computational foundations of high-strain problems are not usually translated accurately into codes designed for linear elastic analysis of metal materials. In simple linear elastic analysis of plastics, care must be taken concerning exaggerated strains sufficiently accomplished with reasonable accuracy. This encompasses computational methods applied by the code, and in a code it includes type of elements like tetrahedrals which do not report large strains very accurately due to their stiffness (Cogger, 2009). It has been found that modern finite element codes do account for large strain designs with nonlinear codes performing better and have more robust element and material libraries well suited to analysis of plastics (Cogger, 2009). Lab-generated material data, is recommended for use in material properties of the software used to give good correlation between models and the analyzed samples (Cogger, 2009). Literature on both reinforced high strength structural fibre glass and recycled plastic blocks are presented in subsequent sub-sections of this paper.

METHODS AND PROCEDURES
Finite Element Analysis in Simulia Abaqus
Abaqus standard implicit finite element code was chosen for this non-linear problem (Vu-Hoang, Vo-Minh, & Nguyen-Xuan, 2018). Careful development of material models through inherent stepped solutions has the potential to give efficient solutions in comparison to explicit codes (Fantuzzi, Tornabene, Bacciochi, & Ferreira, 2018). The code allows for good degree of user input in material model. The versatility is fostered by user defined material cards in Abaqus input decks, which result into control within elastic material constants applicable in analysis (Sridharan, 2017).

Material model chosen for carrying out analysis was plastic Type=Lamina. This model helps to define a single ply of isotropic lamina by use of plastic material characteristics. This model include the switch, Dependencies=3, giving user controls on plastic constant at the beginning of load increment (Degefe, 2015). Three field variables were used in defining values given to material characteristics, compared to original, un-deformed, states. Field variables are flags ranging from 0 to 1, defining variations of elastic material constants from original state, in first lines of the material models, and lowest values described in the field variable dependent lines of the material model (Pan, et al., 2016). Field variables were set at the beginning of every increment by calling field sub-routine from the user defined field cards (Schrum, 2014).

The elements were four nodal points for quadrilateral shapes. The nodes give description of spatial positions of elements and define normal directions of the building part. The normal is important for accurate laminate ply sequence definitions (Cui, 2017). In process of calibrating and validating model comparing full and reduced integration of each element in Abaqus was carried out. Simulation of test specimens was carried out using element type, S4 meaning stress or displacement elements with 4 nodes and S4Rstress or displacement elements with 4 nodes and reduced integrations (Hutton, 2017). Abaqus stresses/displacements use Lagrangian formulations in which elements displace as per behaviour of constituent materials. Static equilibrium at each integration point is solved through Gaussian Quadrature (Entezari, Kouchakzadeh, Carrera, & Filippi, 2017).

Shell section card is used to define the shell elements in Abaqus. The card gives specifications for shell thickness of element, materials and the through thickness integration points (Ko, Lee, Lee, & Bathe, 2017). Composite parameter helps users in defining
discrete layers and orientations. The types of section definitions are: complex, multiple layered, laminate; they accurately describe shell elements (Dufour, Antolin, Sangalli, Auricchio, & Reali, 2018).

**Structural Design of the Building**

Structural design was done with truss and beams design in wire frame format. Truss had bottom chord with truss span of 5000mm long with three queen posts (vertical members) 1250mm apart. The king post (vertical strut) was 1250mm long. Figure 1 illustrates the truss parts.

![Figure 1: Schematic of truss (Source: Authors)](image1)

There were two webs each joining the node where king post meets bottom chord and the node between rafters and the 650mm high queen posts. The truss structure was designed to be supported by 2700mm high pillars and beams of total length 5000mm.

Cross-sectional areas of both truss pillars and beam was 2500mm$^2$. Purlings of length 2000mm and cross-sectional area 2500mm$^2$ were used. Material for structure (truss, beams, purlings etc.) was defined as reinforced high strength fibre glass with Young's modulus of 20.9GPa and poison's ratio of 0.415. Density of fibre glass was given as

$4.8 \times 10^3$ kg/m$^3$. Each member of the structure was meshed using S4R element type assignment, part seeding and part meshing. Wall was designed with thickness of 225mm. Meshing of walls was done in similar manner to structure. Roof was designed to be of iron sheet coated with polymer resin sheet metal thickness of 30 gauge. The combined wall, roofing and structure of the building were as shown in Figure 2.

![Figure 2: Building showing plastic walls and roofing](image2)

The mesh for the building was as shown in Figure 3. The elements were quadrilaterals mainly of rectangular cross-section.

![Figure 3: Elements of house materials before simulation](image3)

Loading on structure was done by point loads of 500N at nodes of truss. Figure 4 shows pressure loading on walls and roof. Pressure on roof and walls was 1 MPa normal to surface. The pressure was so designed to withstand strong winds and other forces that may result in displacements. Gravity loading was $g=9.81 \text{ m/s}^2$ along the $y$ (or vertical) axis. Gravity loading depended on mass of each part.

![Figure 4: Pressure and gravity forces on wall and roof materials](image4)

**Simulation of Wind Effects**

Wind effects were simulated in Solidworks 2017. Fluid condition was air at standard conditions with both laminar and turbulent flows. Heat transfer rate of walls was set at 10W and wall roughness was set at 0.05. Atmospheric pressure was $1.0135 \times 10^5 \text{ N}$ with humidity of 50%. Initial temperature was 293.2K. Velocity of wind

$V_x = 80, \quad V_y = 80$ and $V_z = 20$.

This may vary depending on the conditions in area where the building is intended. Turbulence parameters were: turbulence intensity of 0.5% and
turbulence length of 0.0395m. Goals included turbulent pressure, forces and velocities. Global mesh was defined for the fluid (wind) and external analysis adopted.

RESULTS
Results of stresses on structure were as shown in Figure 5. The maximum von Mises stresses was $1.582 \times \text{MPa}$. The highest stresses were experienced on horizontal end beams shown by red colour on the structure.

![Figure 5: Stresses on structure](image)

Stresses on the building were as shown in Figure 6. Highest stresses were experienced on the roof materials with the values $1.935 \times \text{MPa}$ which was below the roof material yield strength of $2.56 \times \text{MPa}$. The walls had relatively low stresses of up to $3.226 \times \text{MPa}$. Which is below the yield stress of recycled high density polyethylene material used which had a yield strength of $5.0 \times \text{MPa}$.

![Figure 6: Von Mises stress distribution in the house unit walls and roof](image)

Results of flow simulation showed that velocities increased from the initial values to maximum of 110.406m/s and minimum velocity value was 23.612m/s. Minimum velocities were found at walls opposite to the wall of wind incidence. The results were obtained after 78 iterations. Figure 7 shows velocity trajectories and values. Relative pressure profiles around the building was as shown in Figure 10. Highest pressure attained was $6.45852 \times \text{Pa}$. Lowest pressures (at the dark blue region) was $-9.01195 \times \text{Pa}$. These findings corroborate findings by (Corinaldesi, Donnini, & Nardinocchi, 2015) and (Moretti, Zinzi, & Belloni, 2014).

![Figure 7: Wind velocity profile around the building](image)

CONCLUSION
Simulation results show that high strength structural fibre glass composites and recycled high density polyethylene are promising materials for building house units. Experimentation and building of prototypes can be carried out to ascertain the findings of this research. It is concluded that capacity building in expanding knowledge relating to application of recycled materials in building and construction is a key step to achieve sustainability through provision of low-cost housing. Future research can focus on testing of actual material and production of the house unit.
REFERENCES


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