CRAFTING TECHNOLOGIES

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analyse the environmental impact of contour crafting technology as compared to that of concrete masonry units

Developed at the University of Southern California, contour crafting (CC) is a layered fabrication technology that uses robotic arms and extrusion nozzles. The potential impact of CC in construction became evident after successful experimentation with various construction materials such as clay, plaster and concrete. The technology is at a stage where complex shapes such as curved walls have also been constructed.

The objective of this paper is to quantify the comparative life-cycle embodied energy and CO_2 emissions of a concrete wall built by two different methods: the automated CC technology and a standard manual construction using concrete masonry unit (CMU). Our comparative life-cycle models indicate that CC results in a 75-percent reduction in the total CO_2 emission compared to the manual CMU construction method.

Also, the total embodied energy of a CC wall is reduced by 50 percent over the CMU construction method. The manual CMU method has significantly higher life-cycle energy and CO_2 emission mostly due to transportation, on-site construction and longer construction process and related activities. Our calculations also indicate one-seventh reduction in solid waste generated by CC compared to CMU on a life-cycle basis.

What is contour crafting?

Contour Crafting (CC) was first envisioned as a rapid prototyping process aimed at fabricating large-scale parts (Khoshnevis, 1999, 2004; Khoshnevis and Bekey, 2003). CC uses computer-controlled extrusion and trowelling simultaneously to achieve smooth and accurate free-form surfaces.

The process forms smooth external surfaces of the object by constraining the extruded flow onto a solid trowel surface. The trowel orientation is dynamically controlled to conform to the slope of the surface features. Thus, regardless of the surface geometry, the fabricated surface is always a ruled surface because the side trowel always forms a tangent plane to the surface that it forms. Note that the side trowel can change its orientation through deflection during fabrication. If the side trowel changes its orientation then the bottom base curve changes accordingly, but the ruling remains the same.

The key feature of CC is the use of trowels in conjunction with a robotic extrusion system. Artists and craftsmen have effectively used simple tools such as trowels, blades, sculpturing knives and putty knives to form materials in a paste form since ancient times. Despite the progress in process mechanisation with computer numerical control and robotics, these simple tools are still being used manually in model building and plaster work.

In CC, computer control is used to take advantage of the superior surface-forming capability of trowelling to create smooth and accurate, planar and free form surfaces. CC is a hybrid method that combines an extrusion process for developing the wall surfaces and a filling process (pouring or injection) to build the wall core.

The CC nozzle can deliver paste materials and is equipped with a trowel. As the material is extruded, the traversal of the trowel creates smooth outer surfaces on the layer. The nozzle or the trowel can be deflected to create non-orthogonal surfaces. The extrusion process builds only the outside edges (rims) of each layer of the wall. After the complete extrusion of each closed section of a given layer, if needed, filler material can be concurrently poured to fill the area defined by the extruded rims.

At the same time, new rims will be built by the troweling method. Extensive experiments have been conducted to optimise the CC process to produce a variety of 2.5D and 3D parts with square, convex and concave features, some filled with concrete.

More recently, a CC machine was designed that is capable of building full-scale wall sections out of conventional concrete. A number of non-traditional construction projects are being tested using CC as well. For example, CC is being currently tested to build habitat or storage structures on the moon and Mars for example, dome structures constructed with lunar regolith simulant material at NASA Marshall. However, as CC is being considered for large-scale applications in the construction industry, questions have been raised regarding its environmental impact as compared to other standard construction techniques. Animations and videos of the CC process may be viewed at www.contourcrafting.org.

The objective of this study was to quantify the comparative life-cycle embodied energy and CO_2 emissions of a concrete wall built by two methods. The two techniques being compared were the automated CC technology and standard manual construction using concrete masonry unit (CMU).

Life-cycle environmental impact analysis

One measure of success for the application of automation technology to construction is its ability to reduce the total environmental impact on a life-cycle basis. A widely used modelling approach for such multi-phase assessment is life-cycle assessment (LCA), which was standardised by ISO 14000 and SETAC in the 1990s. LCA is most aptly described as a systematic methodology for the identification of environmental impact and consequences. It is applied over an appropriately defined the life cycle, and comprises certain specific elements and assumptions.

Moreover, such comparisons should be made using similar functional units of performances. The life-cycle phases under consideration were concrete extraction and manufacturing, transportation and robot on-site electricity use. In addition, the wall models were the same for both construction techniques in terms of design functionality and the amount of concrete used.

Design characteristics and life-cycle assessment assumptions

The CC design was a simple house design with hollow walls. The walls were designed with interior corrugated features made with a single cantilever robot.

For the CMU house, the walls were made out of concrete blocks. In terms of basic materials, CMU uses a standard masonry block unit with Portland cement as the primary material. The CC house uses ready-mix concrete as the main construction material. Other assumptions and exclusions are listed below.

To reduce the LCA complexity, the following consequences were not addressed in this study:

- Impact of site location on the surrounding ecosystem
- Energy/materials related to landscaping, irrigation, etc
- Embodied energy of the raw material production

Also, the impacts from the following sources and processes were not included in this comparative study because they were assumed to be equal for both methods:

- Use phase energy consumption
- Materials maintenance and improvement
- Wall demolition after its useful life
- Recycling of materials and transportation to landfill

For the purpose of this study, BEES 4.0 database was used extensively for the CMU approach. One limitation of BEES is that it does not contain the emission and embodied energy for the production phase.

We have manually extracted and calculated this information from the Portland Cement Association life-cycle inventory database (Marceau, et al, 2007). To increase data reliability and reduce computational error, the CMU data were extracted from CORRIM (Consortium for Research on Renewable Industrial Materials). The DOE's National Renewable Energy Laboratory database was also used for data unavailable elsewhere (NREL, 2008).

Results of the study

Our first analysis included calculations for constructing walls of a house, comparing the two methods. To begin the analysis, a Bill of Materials was generated for each construction method. Based on each material composition and amounts, raw material inputs were calculated. Using the available life-cycle

Table 1: Summary of CO_2 emissions (kg) by life-cycle phase

Phase	CMU	CC
Extraction, transportation and manufacturing	1.32E+05	1.27E+05
To and on-site transportation	4.58E+05	1.97E+04
On-site construction	-	1.46E+02
Total	5.90E+05	1.47E+05

Table 2: Summary of embodied energy (GJ) by life-cycle phase

Phase	CMU	CC
Extraction, transportation and manufacturing	7.92E+02	7.02E+02
To and on-site transportation	2.90E+03	1.18E+03
On-site construction	-	8.64E-01
Total	3.69E+03	1.88E+03

Table 3: Embodied energy (GJ) and CO_2 (kg) for a square foot of wall

Environmental impact	CMU	CC
CO_2	13.62	3.34
Embodied energy	0.08	0.04

Table 4: Solid wastes (kg/ft^2) during manufacturing and construction phases

Phase	CMU	CC
Manufacturing		
Concrete solid waste	3.89E-02	1.38E-02
Blast furnace dust	1.19E-03	1.17E-03
Blast furnace slag	5.80E-03	5.70E-03
Sub-total	4.59E-02	2.06E-02
Construction		
Concrete solid waste	9.81E-02	0.00E+00
Sub-total	9.81E-02	0.00E+00
Total	**1.44E-01**	**2.06E-02**

databases mentioned above, we generated a set of tables for the embodied energy and CO_2 emissions for each life-cycle phase. The summary of CO_2 emissions and embodied energies for CMU and CC by phase of activities are given in Tables 1 and 2.

The above tables contain data for all the walls in a house. We then reduced this calculation for a square foot of a wall. This was done to make the comparison on a per unit basis, which is easier to transfer to other applications. Table 3 shows the results of this analysis for both CMU and CC methods. For a square foot of wall construction, CC reduces the total life cycle CO_2 by 75 percent and reduces the total energy by 50 percent, as compared to the CMU wall construction method.

With respect to the solid waste, we calculated the total solid waste generated by each method for a square foot of wall, as shown in the Table 4. The total solid waste for CC is one-seventh of that of CMU during the two life-cycle phases of manufacturing and construction. It appears that the CC construction technology has significant advantage over the current CMU approach in terms of CO_2 emissions and embodied energy on a comparative life-cycle basis.

A further look at the data showed that the environmental advantages of CC are a result of less total material use, less total energy required for all construction activities, less transportation of material, equipment and labour and lower material and energy waste during construction.

We believe that the trends toward reductions in greenhouse gas (GHG) emissions and energy use could strengthen the position of this new technology in the future. In addition to constructing walls in standard structures, we foresee applications such as visual and sound barriers, security walls for large areas such as ports and government complexes, flood barriers and landscape borders.

References

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