FERROCEMENT SOLUTIONS FOR AFFORDABLE HOUSING PROTOTYPES IN INDIA

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Abstract: In achieving ‘Housing for All’ in the rapidly urbanising Indian context, ferrocement technology promises to be environmentally as well as economically ‘affordable’, consuming significantly less quantities of building materials with high embodied energy. Though already used to some degree, ferrocement would make its most significant contribution if used for roofs spanning the whole structure, or speedy wall-systems with built-in furniture. Form development plays a big part in the design of ferrocement roofs. Shell structures though efficient, mean complex, expensive formwork, whereas folded-plate structural systems consist of planar surfaces and often easier to construct. A range of geometries are already tested in origami (the ancient art of paper-folding) to stiffen thin sheets of paper, and origami crease patterns serve as inspiration for self-supporting roofs. The paper discusses prototypes designed by the author, for quick and cheap delivery of houses, with alternatives for small and larger roofing spans for residences and community buildings respectively. The prefabrication process, undertaken in backyards of masons’ houses improves social and economic sustainability performance, while the technical design of units improves environmental performance. Developed through Indo-German collaboration, test prototypes were built in Delhi, Chennai, Auroville India; Brisbane and Sydney in Australia; as also in Bielefeld, Berlin and Steinhagen near Bielefeld in Germany.

INTRODUCTION

Given the nature of India’s population and unprecedented current rate of urbanization, the need for environmentally sustainable buildings cannot be overstated, and affordability is a major concern. While the per capita resource consumption is lower than many countries, India’s population creates demands that the nation is struggling to meet. Buildings in India need to be produced with significantly less than globally accepted standards, particularly for the bulk of the construction needs (housing and small public buildings).

In India, steel and cement are not only considered high-energy materials, but they are also costly, need expensive infrastructure to produce and transport and are in short supply. Use of structural ingenuity and engineering is most required therefore to produce lightweight efficient structures that use significantly less quantities of materials, apart from judiciously selecting materials based on their low environmental impact. Moreover, increasing the labour component, paying by including participation of ‘unskilled’ labour will create socio-economic benefits to the local area through a holistic and contextual approach to sustainability.
Ferrocement technology promises to be environmentally as well as economically ‘affordable’, consuming significantly less materials. Though already in use to some degree, the full potential of ferrocement as a relevant and appropriate material in the housing sector is yet to unfold. Significantly lighter than reinforced concrete, ferrocement contributes best if used as the central material for construction of roofs spanning across the whole structure as also if used to construct wall-systems with built-in furniture, leading to great economy of time and cost. Prefabricated or cast in situ varies according to the advantages in each for context. This paper discusses the design of ferrocement building systems developed by the author in response to the growing concern of affordability of housing in India in economic as well as environmental terms. These were developed over the last 3 years through extensive research and full-scale prototyping in Delhi, Chennai and Auroville within India; Brisbane and Sydney in Australia and also in Steinhagen near Bielefeld, Germany. These investigations were deliberately carried out in contrasting contexts, representing developing and developed countries; the contexts being either labour-intensive or material-intensive; and familiar with fine handmade construction, or construction with sophisticated or hi-tech tools.

FERROCEMENT’S PARTICULAR APPROPRIATENESS TO AFFORDABLE HOUSING SOLUTIONS IN DEVELOPING COUNTRIES

Given its thinness as compared to reinforced cement concrete, and its resulting lightness, there is a significant reduction in the consumption of commonly available materials like sand; cement and wire mesh leading to reduction of costs related to materials used. The labour component, which is always a variable in the cost of construction, being comparatively cheaper in developing countries, however makes this technology particularly suitable and attractive for applications in the context of developing countries. Further, skills for ferrocement fabrication can be quite easily acquired. Ferrocement’s mass is much less than RCC, and its dense reinforcement makes it self-supporting even in the beginning of the curing period, making the construction of formwork unnecessary. This is an inherent advantage in the efficiency of time and material. A module, which can be prefabricated, will lend itself to mass-production.

A low-cost, low-tech technology, that has low-maintenance, high durability, high strength when properly shaped, water-resistance, and has the ability to take on almost any form and is easily repaired, ferrocement is versatile in many parts of the world. The American National Academy of Sciences report of 1973 recommends applications in developing countries, including low-cost roofing and disaster relief, and recommended an international committee to coordinate its research and development. Apart from identifying its particular appropriateness to developing countries, it also identified the need for further research and experimentation in not only design but also in production techniques that are contextually appropriate. “Its use, particularly in developing countries, must be preceded by more research and experimentation in design and production techniques suited to construction by unskilled labor.” (Roumaldi 1973)

TWO PARALLEL AREAS OF RESEARCH AND EXPERIMENTATION

The design and construction of affordable housing prototypes in this paper are classified into 2 series according to the differing nature of the problems and solutions within the
housing sector. Housing units themselves involve fairly small spans and room sizes, while needing a complex understanding of ergonomic requirements as very diverse activities and related furniture need to be accommodated within a small space, with a great flexibility of uses across the day as well as across the different needs of different users. On the other hand community buildings related to housing require more complex solutions for spanning larger room sizes, whereas the multipurpose activity spaces contained within these are relatively simple as there is a larger available space and more uniform use within them. The first series of design research and development for large span community buildings within housing projects, particularly their roofing system is called ‘Light Matters’, while the second series focusing on prefabricated elements assembled to form the house itself is called ‘Full Fill Elemental Homes’. Together they contain the basic vocabulary and elements required in the speedy and affordable construction of housing as a whole, as an integrally sustainable approach, that is generally appropriate to developing countries but particularly relevant to the India context.

‘LIGHT MATTERS’: USING ORIGAMI CREASE PATTERNS FOR FORM DEVELOPMENT OF FERROCEMENT ROOFS

In order for ferrocement to be able to span large roofs, its folded geometric form is a key aspect of the design. The design process involves the exploration of folding and bending patterns inspired by origami to lend strength to thin sheets of material, helping it to achieve rigidity and enabling it to support itself.

Bending and folding, the basis of structural stability and form development

Thinness is an essential characteristic of ferrocement and can make this material unstable without introducing folding or bending into its form. Abercrombie aptly describes the material’s relationship to its architectural form thus: “Ferrocement’s thinness makes it structurally unstable without bending, but it is also its thinness, combined with the great pliability of its supporting wire mesh that makes such bending very easy” (Abercrombie 1977).

Form development thus plays a big part in the design and structural stability of ferrocement roofs. Though efficient, shell structures mean complex, expensive formwork; whereas folded-plate structural systems consist of planar surfaces and often easier to construct, and also easier to describe geometrically. The principle of folding to strengthen thin sheets has been known for a long time. While aerospace and the automotive industry use this principle to create self-supporting wall, slab elements with high load capacity etc; in contrast, in the building industry, the principle of folding is less prevalent as perhaps these forms are less suitable for habitat use despite their structural efficiency and more extensively used for large span structures such as auditorium, stadia and industrial structures (KUNDOO, RANGARAO 2013). Due to its properties, ferrocement lends itself to curving or undulating forms and therefore has great potential to be explored architecturally.

The structural resistance of folded plates relies on their edges. These structures are made of plates jointed in certain angles by shear resisting connections. The edges of the folded plates are line-like supports when each plate acts as a slab transferring the load by bending (Fig. 1). All the loads prefer to be supported by the stiff short span and not by the long span of plate. The second main aspect of the structural behavior is that these reaction forces at the line like supports are in equilibrium with membrane forces such as normal and
tangential forces acting in the plane of the plates. Especially longitudinal prismatic foldings spanning in one direction as in (Fig. 1) behave as girders with a thin walled but deep cross section made of flat panels. They provide high stiffness and low deflections by very effective, material saving und economic cross sections.

Figure 1: Load bearing of folded plates by 1) bending of a slab, 2) membrane forces in the plate and 3) frame or truss action. (Source: Büttner, O.; Hampe, E. (1984): Bauwerk, Tragwerk, Tragstruktur. Band 2, VEB Verlag für Bauwesen, Berlin)

THE RELEVANCE OF CREASE PATTERNS FOUND IN ORIGAMI

Origami, the Japanese ancient art of paper-folding transforms flat sheets of paper into three-dimensional forms through multiple folding, and could serve as inspiration for exploring forms for self-supporting ferrocement roofs: firstly to take advantage of the range of possibilities already developed that has continued to evolve and be applied in current times by mathematicians, scientists and artists, secondly to find a way of building synthetic surfaces that integrate roofs and walls; thirdly to translate curved shells into faceted surfaces that can be easier to describe geometrically and easier to build including formwork; fourthly to arrive at forms that contribute to minimum wastage. Origami forms are developed out of a sheet, as also chicken mesh or panels used in formwork, remaining continuous surfaces even though the polygons join other polygons in a different plane (KUNDOO, RANGARAO 2013). Origami can be a very befitting entry point, an intuitive and spontaneous approach to explorations of suitable forms for ferrocement surfaces integrating roofs and walls, where the ‘art of folding’ itself unfolds the structural behaviour.

Selected origami crease pattern and chosen form for prototyping as roof surface

Paul Jackson’s book, ‘From sheet to Form’ formed the basis of the quest for appropriate form to be taken up for development as a synthetic roof surface prototype. After constructing all relevant forms in paper, observing their stability and investigating their suitability to habitation related requirements, the form selected was as shown below in (Fig. 2 to 8). The flattened paper consisted of vertical creases in one direction and diagonal creases in two directions such that the intersections of the thus formed rhombus shapes intersected with the edges of the rectangular sheet of paper. The form was ideal due to its regular geometry and stability but also as the geometry of the open form contained 2 parallel edges in the front elevation which would be ideal to locate a door, while when completely folded it formed a regular hexagon. The form was complete and regular when flattened before creasing, when completely folded, as well as when positioned as a shell.
Force mechanisms in the proposed structure
These folded plate structures are loaded by self weight and wind loads, in some areas snow and earthquake are also an issue. In many cases the self weight governs the design of this folded plates stressed by membrane forces acting in the plane of the plates. The local bending in the triangular plates is of minor importance.

Formwork. And a version without formwork
The fact that this form can be deployed to obtain a smaller more compacted object than the unfolded surface opened up a whole new area of research into deployable formwork that is made of recycled cartons (Fig. 9, 10, 11). This meant that form work which is often a hurdle being time consuming but also expensive, could now be very easy and affordable. Given that the form was stiff for paper, the enlarged full-scale form was likely to be stiff enough if produced in recycled carton. As the form work and steel mesh can be collapsed and transported, it may be ideal also for disaster relief and speedy constructions. This form has the promise of enabling many further areas of economy in time and cost.
First prototype tested in Auroville, Tamil Nadu

The first prototype, later left behind as childrens’ pavilion, was constructed in a residential community called Citadines, in Auroville’s city centre, first in reused corrugated carton. The dimensions and sizing were based on habitation requirements as well actual materials to avoid wastage. A range of alternatives were tried for easy fabrication of steel mesh as well as workmanship issues in plastering the surface from two sides. Finally due to as yet unresolved issues at that stage, the first prototype was made without formwork, breaking down the identical rhomboid elements into separate frames and erecting them in situ to be plastered from both sides. The basic module was a rhombus folded across the longer diagonal. Modules were made in the steel workshop using 8mm dia bars of tor steel with two layers of GI (Galvanized Iron) chicken mesh (22 standard wire gauge, 0.8 mm dia) on either side (Fig.12). Frame panels were arranged in position easily as the side elements were absolutely vertical and the 2 further sloping panels automatically met at the centre where they leaned towards each other. Wooden logs supported these in position during welding. Masons applied cement plaster 1:2, on either sides of the self supporting mesh surface without formwork and cured for 10 days. This proved to be fairly quick and easy and was completed in 4 days (Fig. 13).

Second prototype tested in Sonepat near Delhi, India

A second prototype was built in Sonepat near Delhi at Gateway College campus that hosted the student convention, NASA, and built at the entrance area of the architecture building (Fig.14). The key improvement in the second prototype was to improve the quality of plastering in terms of achieving a thinner section not exceeding 25 mm. The surface was also raised on 450 mm high walls to achieve a higher space.

Further structures constructed for exhibitions in Australia and Germany

A 1:1 scale model of the above was further developed at UQ in Brisbane after solving as a residential unit. Under the exhibition ‘CUSP: Designing into the next decade’ this research was showcased as part of 12 designers whose works were considered relevant for the future, and toured 7 Australian cities. In the meantime, a further full-scale structure ‘Light House’ was exhibited as part of ‘The new modesty: an architecture of restraint’ at the Kunsthverein Bielefeld and DAZ Berlin. showcasing the work of 5 international architects (Fig. 15, 16). Constructed with styrofoam of the same thickness it represented spatial authenticity but was accompanied by a sample of the actual ferrocement. After dismantling the structure was taken to Steinhagen (Fig.17) at the request of a public school that wished to ex-
experiment further by using the styrofoam as a formwork to cast a ferrocement structure and serve as a pavilion for the school students. The research was conducted in different countries representing the two extreme ends of current trends in habitat and urban development globally. To produce prototypes simultaneously in a developed country context and another developing country context addresses its relevance in each context given the huge differences in socio-economic scenarios as well as in population densities and natural resources.

Figure 15, 16, 17: Exhibitions of ongoing investigation at Sydney, Australia, Bielefeld and Berlin, Germany 2013, Prototype at School in Steinhagen. (Source: Anupama Kundoo)

FULL FILL ELEMENTAL HOMES

‘Full Fill Elemental Homes’ are envisioned as speedy and affordable solutions to constructing housing and toilets that have low environmental impact, using an appropriate combination of sophisticated and low-tech. Consisting of specially designed modules of prefabricated ferrocement hollow block units, it can be assembled on the site in less than 6 days including foundation.

Figure 18, 19, 20, 21: Ferrocement production in Masons houses, prototype ferrocement elements for housing and finished housing prototype. (Source: Anupama Kundoo)

Since folding is involved in giving strength to thin ferrocement elements, the concept is based on ergonomically designing folds that form open box units that can be utilised to fulfil and accommodate a range of ancillary storage needs that are fundamental to the efficient performance of small dwelling spaces. The voids created inside the blocks are designed to efficiently accommodate all storage needs of the user, from clothes to books to kitchen utensils, even the kitchen sink itself, and other belongings so that all furniture becomes redundant. The void of the spaces can remain empty of furniture or sanitary fittings, and therefore achieve more space while saving the additional cost and time involved in furnishing homes. Small spaces are often burdened by the way furniture occupies them but these units make small spaces smart using the thick container walls to their full capacity, to
be filled by the residents. The 25 mm thick ferrocement elements involve chicken mesh, welded mesh and small diameter steel reinforcement, significantly reducing the quantities of high-embodied-energy materials used in the construction. Blocks are produced in the backyards of masons homes to provide them with additional income, rather than in factories, thereby reducing costs while helping local economy. A range of window, doors, roof elements and other necessary building components are all produced in ferrocement excluding any complex hardware in their design. The voids in the walls that can be colonised by the users, are emphasised, rather than the walls themselves, through the use of the happy colours. Roofs for the housing and toilet units consist of moulded prefabricated interlocking U shaped profiles according to the size and weight restrictions involved in easy transportation and assembly.

The prefabrication process, undertaken in backyards of masons’ houses improves social and economic sustainability performance, while the technical design of units improves environmental performance. Affordability is due to efficiency and inclusivity. Rather than producing the elements in a factory, the elements are produced in a decentralised arrangement in the home backyards of masons who are assisted by their helpers. This idea has already found enthusiasm in the villages around Auroville, South India where local masons have ferrocement experience. Masons can conduct training for other masons in the villages who want to participate. The pieces are checked for quality through a local engineer, and directly delivered to the site for assembly creating further economy. The design is suitable for all, not only the poor. The structures can be used as immediate shelters necessary in farm house plots in remote areas, disaster relief homes, youth hostels, student housing, as well as guest houses in environmentally sensitive locations. The houses can be dismantled equally simply in a day.

India has a huge housing deficit and an acute shortage of toilets not only in urban areas. Most available solutions take too long to construct, have cost-escalations by the time they are delivered, and are not affordable to the target group. India has a huge demand for prefabricated solutions to housing, toilets and other buildings that are affordable not only in money terms but in terms of all other natural resources. There is a demand for decentralised solutions that are environmentally low impact and for an appropriate balance between high-tech and low tech approaches given that many areas have no access to stable electricity, and given the level of skills and knowledge of a large section of the population. Full Fill elements are designed as a quick response to the above demand. Given that the units are prefabricated and involve an assembly in less than 6 days in most cases, there will not be any cost escalation reassuring the target group who are investing their precious funds to meet their housing and sanitation needs. As the elements are built using materials and skills that are universally available, the same system designed and investigated for Tamil Nadu state is replicable across the country, regardless of urban or rural areas, or climatic zones as these can be easily produced in both areas and continue to be advantageous everywhere.

Since the proposed construction system will be significantly cheaper and quicker to construct, the main impact will be a quick reduction in the urgent demand for housing and sanitation solutions across the rapidly developing country. This reduction will not come with a negative environmental impact but rather provide solutions and set new consumption standards for building construction in the future. The system requires no initial investments, no factory space for production and no storage space, the economic benefits are
significant. Geometry and engineering know-how delivers the maximum built space for the least use of materials as the form of the product contributes to its strength. The material reduction involved in using ferrocement technology makes it extremely reasonable compared to other prevalent building technologies. Steel reinforcement bars are replaced by steel mesh; 25 mm thick wall elements are used instead of 125; and the economic benefit is proportional.

Socially there are many benefits too. The skill can be easily acquired. Masons and helpers can produce these elements in the various backyards of their houses rather than in a factory. They can work according to their need and in flexible hours or weekends there by having an additional income source for days when they are not occupied on a daily wage labour. They are part of a larger craft-network managed by a local sustainable construction company, and their pieces are quality controlled by visiting engineers and supervisors. Since steel mesh replaces reinforcement bars, all materials can be easily sourced locally and can be bought in small quantities according to the need. Expert masons can also choose to work as trainers for others desiring to produce ferrocement elements at their home yards.

Environmentally, the system offers a low impact solution as it uses far less resources than regular standard construction by replacing steel bars with steel mesh, but also by using very little material at all given the thin construction elements. As these are complete elements there is no need for any additional finishes like plaster and paint. The units come with storage space built in, so this makes the budget for furniture redundant. The units are durable, but can also be dismantled in a day if necessary and the site can be left as before with no negative impact. The dismantled units can be reassembled elsewhere. Transportation energy and use of electricity are minimal, cow-carts suffice where these are available. Production is decentralised and develops and uses local skills. An integral development solution, such an enterprise generates local economy, spending a small percentage of the budget on materials and a large part of it on the labour, thereby benefitting livelihood while providing quick and affordable solutions to toilets, houses and other spaces. As the elements are individually hand-made and not standardised factory mass-produced ones, there is a great advantage in that tailor made solutions or colour options do not come at an extra cost.

**FURTHER WORK**

Abercrombie wrote in 1977: “Compared to other building techniques, ferrocement has remained a puzzling freak. Its design criteria are based mostly on experience, not on scientific experiment, and without accepted data to explain its unusual properties, those properties have gone regrettably underutilized.” Through a combination of theoretical research and continued hands-on full-scale experimentation on site, further research and investigation of the above proposals will continue in Madrid and Berlin, with the assistance of engineers from TU Berlin, and the team of craftsmen in India supervised by a local engineer and architect. These prototypes which have been preliminarily executed in India are being further developed for introduction to the main-stream after thorough testing with European standards. The next step is design optimisation, to streamline the product and arrive at further economy and efficiency before introducing this as a versatile housing solution in the rapidly urbanising world.
CONCLUSIONS

The above explorations use Ferrocement as the central material in construction unlike current uses as secondary elements. The wall and roof systems allow quick construction and examine shelter or the building envelope as a synthetic solution of a single surface, without categorizing this as wall or roof, leading to further economy and efficiency, particularly in the case of larger spans. These proposals are holistic aesthetic solutions to affordable construction not only in money terms but also in environmental terms. A low-cost, low-tech technology, that has low-maintenance, high durability, high strength when properly shaped, water-resistance, the ability to take on almost any form and is easily repaired, ferrocement can prove to be a versatile material to address affordable housing and could be relevant beyond India, in many parts of the world.

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