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STRUCTURAL FRAME SELECTION PROCESSES: CASE STUDIES OF HYBRID CONCRETE CONSTRUCTION PROJECTS

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ABSTRACT

Selection of the most appropriate structural frame for a building during the conceptual design stage is crucial to the overall performance and value delivered to the client. Despite this, the decision making process is commonly characterised by subjectivity and heuristic reasoning making it difficult to map / analyse the factors underlying structural frame selection. This paper uses both live and retrospective case studies of Hybrid Concrete Construction (HCC) projects to gain an understanding of decision making for structural frames. These two case studies represent different building types: one is bespoke; and the other is a more standardised type of building. HCC comprises a combination of in-situ and precast concrete elements. Interviews with relevant members of the project teams were used as the main data collection technique. This paper explores various stakeholder views on the reasons for adopting a particular solution, and the particular challenges associated with the use of hybrid concrete. Although the small sample prevents generalisation to a wider population, the findings suggest that HCC is used for buildings where cost and time performance are not the most important criteria, but where architectural aesthetics and longer-term issues, such as sustainability prevail. Clients and architects were found to be the most influential team members in the frame selection process. Due to the increased complexity of HCC projects, team members need to be involved early and, most importantly, adopt a cooperative attitude which should be nurtured throughout the duration of the project. These findings provide useful lessons learnt and highlight the implications for practitioners using hybrid concrete structural frames in the future.

Keywords: case study, design decision-making process, hybrid concrete construction, structural frame.

INTRODUCTION

In providing the underlying form of a building, protecting occupants against environmental forces and (quite literally) supporting their activities, the structural frame is undeniably an essential element of any building. The appropriate selection of materials, configuration and capacity of such a frame is vital to the short and long-term success of the building. In the short-term, the frame must satisfy the client's needs such as construction completed on time and to budget. In the long term, it must permit, for example, the degree of flexibility required by the same client. The final choice is of particular significance since the frame interfaces with many of the other elements of the building, thereby having a tangible impact on their specification and buildability.

Studies of current practice with regards to frame choice indicate that selection criteria tend to focus on cost and time requirements (e.g. Idrus and Newman, 2003). Although these two criteria are important and should not be detached from any business endeavour, they are not sufficient to accommodate various issues related to user needs and requirements pertaining to the service-life of the building. Furthermore, structural frames tend to be selected based on heuristic decision-making processes dominated by subjectivity and qualitative reasoning (Ballal and Sher, 2003). This complexity may be magnified further with the involvement of various stakeholders and consequently affected by their decisions. Cumulatively, project teams seem to miss opportunities to learn useful lessons and to widen their choices for structural frames for future projects. A more objective, transparent and systematic selection process might help the construction industry in general to deliver consistent high quality products that better meet client expectations.

Traditionally, construction has long been characterised as suffering from a lack of innovation and being slow to adopt new ideas and technology: factors that have been regarded by some as the reasons for a lack of performance (e.g. Egan, 1998). To accommodate ever-increasing user needs and requirements, it is essential that the industry explores new structural frame technologies on offer, such as Hybrid Concrete Construction (HCC), here defined specifically as the combination of in-situ and precast concrete (Goodchild, 1995; Glass and Baiche, 2001). HCC aims to offer all the benefits of using each individual element, whilst compensating for the individual weaknesses of those same elements. For example, Goodchild (1995) argued that an in-situ reinforced concrete frame is often regarded as the least expensive solution, whereas precast concrete promotes speed and high quality. The combined solution has the potential to provide greater speed, quality and overall economy. Nevertheless, authoritative criteria to assess the potential of this technological innovation have not been clearly defined. Once established, the criteria would allow stakeholders to realise the benefits of using such innovations and thus increase the frame options available to them.

One live and one retrospective case study of HCC projects were used to gain an understanding of the decision making process for the selection of the most appropriate structural frame. These two projects formed part of a scoping study aimed at identifying the heuristic decision-making processes inherent in the structural frame selection process. As these two case studies represent different building types (i.e. one is bespoke and the other a more standardised building), they have provided useful

lessons and highlighted the implications the practitioners need to take account of when considering the use of hybrid concrete structural frames. Ultimately, the potential benefits of using HCC to deliver better value for construction clients have been highlighted.

HYBRID CONCRETE CONSTRUCTION: A TECHNOLOGICAL INNOVATION

HCC is sometimes referred to as ‘mixed construction’. In the UK, the use of HCC technology is still in its infancy (Glass and Baiche, 2001) and, therefore, there is a need to promote its wider take-up by the industry. The technology itself has been around for some time but it may be new to many potential adopters. The challenge is to diffuse this innovative technology by promoting its benefits and communicating the associated risks in relation to its adoption. HCC offers several advantages that could be considered as the drivers to adopt this technology. Potential adopters of HCC could assess relative advantages of this technology against predetermined criteria. Based on interview data analysed using a cognitive mapping tool, Barrett (2001) identified salient criteria for contractors in their choice and use of HCC (in descending order of importance): aesthetics; function; speed; responsiveness; safety; integration; buildability; and confidence. Aesthetics and function are about the ‘product’ and are amongst the strongest points for adoption of HCC technology, whereas the remaining criteria deal with the ‘process’ (Goodchild 2001). Goodchild (2001) demonstrated that the costs for HCC were broadly similar to those of conventional construction, therefore, this criterion should not be a major influencing factor in the selection process. Glass (2002) identified HCC performance indicators and classified them into those of ‘higher’, ‘medium’ and ‘lesser’ importance: ‘higher’ importance indicators include speed and cost; ‘medium’ importance indicators encompassed spans/lettable area, flexibility in use, fire and service integration; and ‘lesser’ importance indicators comprised buildability, environmental, finish, quality, site conditions, structure, market conditions and safety. Soetanto *et al.* (2004a,b) compiled a set of HCC performance criteria and proposed a systematic evaluation method that permits hybrid concrete frames to be evaluated transparently and objectively against other alternatives. Later, Soetanto *et al.* (2004c) found that ‘physical form and space’ of a building, ‘meeting perceived needs’, and ‘construction cost and safety’ to be important factors in the selection of appropriate structural frame. This suggests an emphasis on building design as well as construction process for promoting the use of HCC. In a similar vein, Glass and Baiche (2001) argued that achieving the potential benefits of HCC would mostly rely on the smoothness and efficacy of the management of design, procurement and construction processes.

A conceptual adoption model for HCC technology

In addition to the specific HCC literature described above, a body of literature in related areas such as diffusion of innovation, technology transfer, organisational innovativeness, industry environment and barriers to innovation, reviewed and presented in ART of LSW (2003), suggests that there are many factors that may influence decision to adopt a particular type of technology, such as HCC. In order to allow greater understanding of these, a conceptual model for HCC technology adoption has been developed. The model suggests that the decision to adopt HCC technology is initiated by the need to innovate which could be, for example competitive advantage, client demand, emerging problems representing ‘drivers of

innovation' which urge people to consider alternative technologies or new methods of working. If HCC technology is to be adopted, these needs should be 'matched' by the benefits of using of HCC, i.e. the characteristics of HCC such as aesthetics, function, speed, safety in comparison with those of existing technology (e.g. conventional in-situ concrete). Since people are more convinced if they could 'see' tangible evidence of these benefits in advance, a means to provide this evidence is needed. A tool is currently being developed to bridge the gap between drivers of innovation and HCC characteristics. This tool serves a pivotal role to expose the benefits of using HCC.

Apart from matching the need for innovation and the benefits of using HCC technology, there are many factors that may influence the take-up of HCC technology. The literature review suggests that factors influencing the adoption of HCC technology could be classified into four categories (ART of LSW, 2003), explained as follows.

- Individual factors refer to characteristics inherent within individual decision makers such as attitude towards change and risk, vocational background, and age.
- Project factors concern project characteristics influencing the use of HCC technology, such as type of project, private or public project, and procurement route.
- Organisational factors are characteristics inherent within the organisation, which determine the receptiveness of the organisation towards a new technology, for example senior management attitude / commitment, organisational structure and culture.
- Industrial factors are the characteristics of the industry that provide an environment and establish rules and boundaries for the operating organisation, for example government policies, building codes and competitiveness level.

These factors indicate the complexity involved when deciding to adopt HCC technology. It is reasonable to assume that these factors do not exert the same level of influence, instead, various levels of influence are to be expected.

The literature review suggests that the widespread adoption of HCC technology relies on: how the potential benefits and its associated risks are communicated to participants in the supply chain; and the factors impeding its use are identified and addressed by devising a mechanism to allow its appropriate take-up. As a first step, it is essential that the decision-making process in relation to selecting an appropriate structural frame be explored and lessons learnt for the future. This paper attempts to achieve this by using case studies of two building projects using hybrid concrete structural frames.

METHODOLOGY

Yin (1994) argued that the selection of an appropriate research strategy is dependent on three conditions: type of research question; the extent of control an investigator has over actual behaviour events; and the degree of focus on contemporary as opposed to historical events. This research sought knowledge regarding *why* a hybrid structural frame is preferred to its alternatives and *how* it is selected, designed, constructed and maintained to meet the needs of building occupiers. The researchers have *no control* over the selection, design, construction processes. The boundaries between strategies are not clear and sharp as demonstrated in this research which has focused on both

contemporary and *historical* (live and retrospective) events. These conditions led the authors to select a case study based strategy.

Two building projects were selected due to their characteristics. Project A was an award winning art gallery building in a city centre, representing a retrospective case project from the 'luxury' market segment of HCC. Project B was an office building and three car park buildings, representing a live case project of a more 'common' utilisation of HCC. Although both projects cannot be considered to represent all possible applications of HCC, they can be deemed typical HCC application. Interviews were held with clients or their representatives, architects, structural engineers, main contractors and precast manufacturers. They were arranged either individually or in a group depending on interviewees' convenience. In the first instance, the interviewees were asked to describe their company and the nature of projects undertaken. The main issues discussed included: the criteria used for selecting the most appropriate frame; why it was preferred; when it was selected; the decision was made; who was involved, the most influential and responsible for the decision; what tool / procedure was used to inform selection process; what constraints prevented certain alternatives to be selected; and finally how well the selection process went. The interviewees were also asked to share their practical experience in design and construction of their hybrid concrete frames. Each interview lasted about one hour, and was tape-recorded and transcribed.

CASE STUDY PROJECT A: THE ART GALLERY

Project A involved the refurbishment of a historic gallery/listed building and a new build project adjacent to another listed building. These three buildings needed to be integrated into one. The project commenced in 1995 and ended in 2002. The budget was £25m and the construction period 4 years. The design was let by open competition, won by the Architect. The Architect is renowned for its prowess and reputation in designing concrete building using precast components. The Architect was also involved in the method of financing the project which was largely funded by lottery. The City Council (the Client) provided matched funding and European region development funding. The procurement route was construction management. It was delayed for six months due to commissioning of M&E services. The structural frame of the new building was mainly a precast concrete frame, however small parts were steel. Initially, in-situ and steel frames were also considered to reduce first cost.

The roles of participants

The choice of structural frame was principally governed by the Architect. Initially, there were two main material choices, namely concrete and steel. The Architect worked closely with the Engineer from the very early stage (i.e. during competition). However, the Engineer had no influence on the selection of type of structural frame. The Client had rather less influence on frame choice decision as they stood by the Architect's decision. As a constraint, the Client stipulated a fixed total project cost to represent the total funding available. The Architect, however, considered the requirements of the User (the management team of the gallery) through various consultations. These requirements mainly focused on: the long-term effect of the material used (i.e. concrete) on the paintings (conservation of important artworks); functionality; and to some extent aesthetics. The requirements for the precast elements were performance-based (e.g. required certain level of reflectivity, colour consistency,

very strict tolerance: $\pm 3\text{mm}$). Once on board, the Architect developed a bespoke concrete mix with the Precast Manufacturer. The Precast Manufacturer was also responsible for resolving connections between precast elements. The Construction Manager provided practical advices on buildability and the manufacture of precast components, specifically in terms of size, joints and connections. Although using precast components, this project did not take full advantage of repeatability for economy as the number of components for each mould was few and the concrete mix bespoke. Nevertheless, the building benefited from high-quality concrete finishes made possible by factory-controlled conditions.

Reasons for using hybrid concrete structural frame

These can be classified into four factors, namely: internal functionality and aesthetics; execution; external aesthetics; and weathering / maintenance. Internal functionality and aesthetics could be detailed as follows.

- Concrete is able to maintain steady thermal mass for the tightly controlled environmental conditions of gallery spaces, which requires more stable (lack of extreme fluctuation in) temperature and humidity. This facilitates preservation of the artwork.
- Finishing characteristics of concrete create a calm aesthetic interior to better display and emphasise the artwork.
- Specific concrete mix to achieve certain level of reflectivity required for lighting without the need to apply finishes (e.g. paint, varnish). The requirement for lighting (to achieve 200 lux) determined the colour of concrete. The Architect and Precast Manufacturer worked together to achieve a balance between minimum amount of lighting and exact colour of concrete to give a diffuse 200 lux. Too much lighting also means using too much energy and increases air temperature, which may degrade the artwork.
- Mouldability of precast allows shape of the floor slab to accommodate lightings, sensors, speakers, spot lightings, cameras, etc. These can be located in the space created by vaults. Smooth surface of concrete diffuses light in the space. This results in an integrated system.

Execution factors were of concern because the project site is located in the city centre. Precast was used instead of in-situ concrete in order to reduce on-site erection time. Furthermore, precast components, produced in a controlled environment, can achieve the tight tolerance required in this project. External aesthetics of the building were considered because the new building was to be built adjacent to two listed buildings on site, which are both made from sandstone. Therefore, the new building should be made from stone or cementitious type of material.

Concrete was also a favourable material in terms of its ability to withstand weathering, requiring minimum maintenance. The art gallery is a landmark building which was designed for a minimum of 60 years. Concrete can achieve longer design life than other materials. In terms of cost, hybrid concrete frame may be more expensive but requires no finishing and minimal maintenance.

Problems encountered

Interviewees expressed problems and challenges encountered from the early design stages through to facility maintenance as follows.

- A Construction Management route was considered not to be appropriate for refurbishment works due to uncertainties involved. This caused interface problems due to contract scope changes with some of the subcontractors / suppliers.
- The buoyant market when construction commenced increased construction costs.
- Communication between the design team and the Construction Manager was somewhat hindered by the location of the design team some 200 miles away.
- Getting the right concrete mix / quality and resolving connection details of the precast components were very challenging. In addition, complex design, limited space and a lot of temporary works made construction very difficult.
- Light coloured concrete floor and glass blocks on the floor posed cleaning and maintenance problems.

Nevertheless, all interviewees expressed satisfaction towards the building and learnt valuable lessons from this project. For example, the Architect learnt how to improve their current precast design from their previous project since the project used precast elements bolted together on site. The Precast Manufacturer invented new systems to bring those precast elements together and to choose the right mix. The Engineer learnt about connections and joints. The User was proud of their bespoke, unique landmark building.

CASE STUDY PROJECT B: OFFICE HEADQUARTERS

Project B was a PFI project aimed at providing a new accommodation for approximately 1,600 employees with facility management for the next 30 years. Generally, the project comprised office buildings and car parks. The total building area was 48,000 m². The site was originally three car parks, a Victorian building, a school and a number of trees. The total project budget is £57.42m, equivalent to £1,195/m². The overall planned project duration was 76 weeks. The project was six months into its programme when the interviews were conducted.

The roles of participants

The Consortium was selected after three stages of evaluation by the Client's project team and their advisors. The Consortium was invited to submit a pre-qualification questionnaire for evaluation by the Client. This evaluation resulted in a list of potential suppliers who were asked to submit outline proposals for the project. The proposal included outline design and details about how the facility would be constructed and managed during the 30-year operational life of the building. The pre-qualified list of consortia were then asked to price their proposals. One consortium was awarded preferred bidder status and asked to develop a full proposal where contracts could be exchanged.

The Consortium comprised the Developer, who acts as a 'client' undertaking the development project, setting project brief and specifications; the Contractor (design and build contractor and planning supervisor); and the Facilities Manager. The Contractor then appointed the Architect and the Structural Engineer. The project involves two precast manufacturers: one for the office buildings; and the other for the multi-storey car parks. Apart from these, the Contractor had an army of potential suppliers/subcontractors, who have worked for them previously based on negotiation. This reflects the Contractor's emphasis on supply chain partnership for better project delivery.

Reasons for selecting a hybrid concrete structural frame

Several considerations have led the Consortium to use hybrid concrete structural frame, as follows.

- The End-user specifically requested a concrete building which was considered to be better able to withstand bomb blast/terrorist attack. Concrete was considered more robust than steel. Moreover, in the case of fire, concrete behaves better than steel, allowing occupiers to evacuate safely.
- In comparison with steel frame, selecting a concrete frame would not significantly affect cost and speed of construction.
- The actual concrete finishes enhance the building aesthetics.
- Concrete contributes positively to the internal office space through its 'thermal mass' characteristics. This reduces the M&E costs, which amount to only 20 per cent of the total construction costs. As a PFI project, the building should be naturally ventilated (a government requirement to reduce operational energy/running costs of public buildings) .

The End-user steered the choice of structural frame material. Considering the other benefits of using concrete and comparison with other materials, the Consortium agreed to use hybrid concrete. As a PFI and design build project, the Structural Engineer and Architect were employed by the consortium, and therefore had less influence on the choice of structural frame material than they might have in more common, traditional forms of procurement.

Practical considerations / challenges associated with hybrid frame

Several attempts have been made to improve performance, detailed as follows.

- The precast coffers were made using steel moulds.
- No in-situ topping was necessary on the precast slabs.
- In-situ primary and edge beams were designed to enhance buildability and speed of construction.
- Reinforcement of the connection at the column head has been rationalised and minimised. Significant design effort was required to achieve this.
- Significant effort went into the design of the precast coffer unit to achieve optimum handling by tower crane. The largest component weights eight tonnes. Three units can be transported on a wagon.

DISCUSSIONS OF FINDINGS

These case projects confirm the main finding of the literature review that the selection of an appropriate frame is very much a heuristic decision-making process based on subjectivity and qualitative reasoning. There was no evidence of objective and systematic procedures in these two case projects. This leads to the conclusion that choice of an appropriate frame is dependent on the intended purpose of the building and parties who are the most influential in the decision making process. Designers (e.g. architects and structural engineers) may have a pre-conceived idea of the structural frame that is the most appropriate for a particular building, or which options are likely. While this intuitive 'feel' for a project may result in an appropriate decision being made, there is a risk that viable, but less well known, options could be overlooked. Hence, in this heuristic decision making paradigm, a lack of awareness of

HCC technology may effectively preclude its consideration as an option for the structural frame.

Specific key findings representing typical conditions and requirements for the utilisation of hybrid concrete frame are as follows.

- Hybrid concrete frames tend to be used in prestigious/landmark buildings. Special requirements (e.g. to withstand bomb blast) may favour the use of hybrid concrete frames due to the characteristics of concrete as a material.
- The decision to use hybrid concrete frame is made at very early design stage. The dominant role of the client and the architect is notable. The structural engineer and contractor appear less likely to recommend this solution. The contractor may employ faster and, maybe, cheaper solutions, such as steel and in-situ concrete frames.
- Cost is not the main determinant for choosing hybrid concrete frames. The criteria revolve around physical appearance, aesthetics and long-term issues such as maintenance, thermal mass and the whole life cycle costing (although this is required in PFI projects).
- Performance of hybrid concrete frames against programme is not particularly better than its alternative due to the lead time to design and manufacture precast components. However, the construction time may be reduced due to shorter erection time. This will also result in fewer activities on site, hence contributing to a cleaner site and better health and safety performance.

The use of a hybrid concrete frame generates specific arrangements and requirements not commonly encountered when using traditional solutions. Hybrid concrete solutions increase complexity in design and construction. All participants of the project should be involved from early design stages to best deal with this complexity. The early inputs from these participants are essential for robust design and smooth project delivery. The knowledge held by the precast manufacturer is very important. This will expedite the project and solve problems before on site activities commence. Getting the precast manufacture's expertise and price earlier will minimise problems later on. To do this, the participants should possess and be willing to demonstrate a cooperative and teamworking attitude throughout project life. The project leader should continuously stimulate these participants' interest particularly during early design where the integration of project team effort is crucial to the success of the project. It suggests that relationship-based procurement routes, such as partnering and strategic alliances, would better support projects using hybrid concrete frame as participants are more concerned with (and have more time to deal with) longer-term issues rather than first cost and speed of construction. These procurement routes would nurture the essential ingredients of a harmonious working relationship, such as familiarity, confidence and trust.

CONCLUSIONS

This scoping study has revealed the nature of the structural frame decision process in relation to two major projects in the UK. If these findings are representative of other HCC projects, there are important implications for both researchers and practitioners using hybrid concrete structural frames in the future. The findings suggest that an appropriate structural frame for a particular building is commonly selected based on heuristic decisions based around subjectivity and qualitative reasoning. Furthermore,

certain parties were found to be more dominant than others. In the case of hybrid concrete frame buildings, clients and architects were found to be the most influential decision makers. This suggests that an appropriate frame is dependent on the intended purpose of the building and parties who are the most influential in the decision making process. The findings also indicate that HCC is used for buildings where cost and time performance are not the most important criteria, instead architectural aesthetics and longer-terms issues, such as security, sustainability and maintenance, prevail. Due to the increased complexity of HCC projects, team members need to be involved early and, most importantly, adopt a cooperative attitude which should be nurtured throughout the duration of the project. The knowledge of the precast manufacturer was also crucial to the success of HCC projects.

The lack of clarity in decision making for structural frames inherent in a subjective approach has been noted as a potential pitfall for new technologies such as HCC. A tool is currently being developed to help improving design decision-making process for selecting an appropriate structural frame. This should enhance the likelihood of less well known technologies being considered on an equal footing during the early stages of a construction project.

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