Empirical Evaluation of Structural Frame Performance Criteria: Realizing the Potential of Hybrid Concrete Construction

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Abstract: Despite its enormous potential to improve performance, hybrid concrete construction (HCC) is currently underutilized. To demonstrate the benefits of using HCC (sometimes referred to as "mixed" construction) within the industry, it is essential that transparent criteria to assess this structural frame type against alternatives be determined, defined, and evaluated. Following a thorough review of literature in the building performance domain, a survey of U.K. experienced practitioners including clients, engineers, architects, quantity surveyors, and main contractors was conducted to obtain their perceptions regarding the importance of structural frame performance criteria (SFPC). A factor analysis of SFPC revealed seven dimensions, interpreted as "physical form and space," "construction process," "long-term sustainability," "establishing confidence," "building impact," "physical appearance," and "client satisfaction." These dimensions should improve the decision making process when selecting an appropriate structural frame during early project stages by providing a simple list of performance criteria to be considered. Although these SFPC and dimensions were originally developed to ensure that the benefits of using HCC were apparent during the frame selection process, they are equally applicable to all frame choice comparisons. As such, they may provide a valuable tool for ensuring added value and client satisfaction.

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Introduction

Construction has frequently been criticized for being slow to adopt innovative ideas and technology, which have been regarded by some as holding back its performance. Recent United Kingdom (U.K.) governmental reports (Latham 1994; Egan 1998, 2002) have highlighted the lack of efficiency, the mediocre performance of the construction industry, and the need for continuous process improvement based on performance measurement. To stimulate the improvement of performance, organizations commissioned by the U.K. government have developed various "official" performance indicators (e.g., key performance indicators, design quality indicators). The industry has been encouraged to learn from the practices and innovations adopted by other industries, such as manufacturing and aerospace. Although the use of standardized fabricated components has been the norm in the manufacturing industry, construction somewhat lags behind in using such components (Gibb 1999). The use of these products promises many significant benefits to construction, such as reduced time and cost, improved quality, and improved health and safety, as exemplified by many of the movement for innovation "demonstration projects" (Egan 2002). Thus, for construction to reap these benefits it is essential that these products and associated methods be explored, adapted as appropriate and subsequently adopted.

One important application of prefabricated components is hybrid concrete construction (HCC), here defined specifically as the deliberate combination of in situ and precast concrete to form a structural frame of building (Goodchild 1995; Glass and Baiche 2001; Glass 2005). HCC is considered as a variant of "mixed" construction (Elliott 2002), the term used to describe a combination of different construction materials or framing methods to fulfill the varying structural requirements of a building. It is advantageous to further describe HCC in relation to the terms "composite construction" and "composite action." The term composite construction simply means different materials being used together in a structure, such as steel and concrete, precast and in situ, or it can mean different materials combined to make a second, new material [e.g., glass reinforced concrete (GRC)]. However, the term composite action has a specific meaning in structural design. This means combining two or more materials in such a way that the resulting construction is stronger than would be obtained by merely adding their strengths (Scott 1991). Hence, HCC may simply be composite construction, but designed appropriately can also offer the potential to provide composite action. It is not common practice to characterize HCC by the proportion of various construction methods (i.e., 20% in situ, 75% precast, and 5% steel), rather the final combination would be based on the most

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effective way in which the client's requirements can be met. Indeed, HCC aims to offer the benefits of using each individual element, hence compensating for individual weaknesses, so many possible combinations exist for HCC. For example, Goodchild (1995) argued that an in situ reinforced concrete frame is often regarded as the most inexpensive solution, whereas precast concrete promotes speed and high quality. Thus, it stands to reason that a combined solution provides greater speed, quality *and* overall economy.

Despite its potential advantages, the use of HCC poses problems and increased complexities not commonly encountered in traditional construction. The principal requirement of successful HCC projects is that project knowledge and design information have to be brought early in the process, and hence greater demand for management task to ensure coordination and involvement of key team members [Reading Production Engineering Group (RPEG) 2001]. HCC is currently under-utilized in the United Kingdom (Glass and Baiche 2001). RPEG (2001) found that the lack of expertise in designing HCC was the key barrier to its adoption. Regarding the use of precast concrete, a main element of HCC, Arditi et al. (2000) suggested that apart from the lack of expertise, the major reason of its underutilization was apparent belief that it would not result in significant cost savings. Goodchild (2001) commented that the costs for HCC were broadly similar to those of conventional construction and therefore, this criterion did not offer an advantage for its adoption. Further, studies of current practice suggest that actual structural frame selection criteria tend to focus primarily on cost and time requirements (Idrus and Newman 2003). This places HCC on an unequal footing with more traditional steel and in situ concrete alternatives. Although cost and time criteria are important and should not be detached from the decision-making process, they are not sufficient to accommodate various issues related to client/user needs and other requirements pertaining to the service life of the building. For example, there is a growing need to consider added value and design quality (e.g., aesthetics, a building's "softer" impacts) during the early project stages (Gann et al. 2003). Thus, to promote its wider take up by the industry, it is vital that the benefits of adopting HCC are realized, understood and disseminated. The first step toward this is to establish a list of structural frame performance criteria (SFPC) which permits an objective and transparent assessment of the performance of various alternatives.

This paper develops appropriate criteria for use by project teams to evaluate the performance of structural frames. The intention was to compile a list of empirically derived criteria that could be used to assess a number of aspects in relation to the selection of an appropriate structural frame during the early design stages (i.e., options study), such as cost, program, value, and aesthetic considerations. The list of criteria include both "hard" and "soft" metrics which may better capture the potential "value" of structural frames, as opposed to the traditional outturn measures of time and cost. This would therefore enhance the likelihood of selecting high quality solutions, such as HCC, when they are the most appropriate for the project in hand. The list of criteria was developed from a comprehensive review of official criteria on construction performance and postoccupancy evaluation of buildings as well as HCC-specific criteria, ensuring comprehensiveness of the SFPC, as well as a need to define SFPC at operational level indicators. The list of criteria were then used as a basis for a questionnaire survey to establish their relative importance. The findings were subjected to factor analysis to group these criteria into several dimensions which aid understanding of the underlying performance of structural frame. These dimensions will help project teams to compare alternatives and determine an optimum structural frame solution for a given situation.

Methodology

This paper is based on the findings of three main tasks, namely the compilation of SFPC, questionnaire design including a pilot survey; a questionnaire survey; and the application of factor analysis, as is explained in the following sections.

Compilation of Structural Frame Performance Criteria, Questionnaire Design and Pilot Survey

An extensive review of literature revealed that there was no authoritative, comprehensive list of performance criteria developed specifically for assessing structural frames. To compile a meaningful list of criteria, an extensive review of literature in related areas was conducted. This included building performance evaluation, postoccupancy evaluation (POE), and various construction-related performance indicators, as well as HCC literature. All such criteria were meticulously evaluated for their relevance to structural frames.

The list of criteria was formatted into a questionnaire, which was designed to capture practitioners' perceptions of the relative importance for each of the proposed SFPC. Prior to presentation of the criteria in the questionnaire, respondents were invited to indicate details of their employer and experience in industry and present company. Additionally, they were asked to assess their company in terms of its receptiveness toward technological innovation, as exemplified by Toole (1994) and their awareness and experience in using HCC technology, as well as the reasons for using this technology.

To justify the list of SFPC and to check the presentation of the criteria in the questionnaire, the research team consulted four practitioners who had extensive experience in structural frame selection processes. Specifically, they were asked to comment on the relevance and comprehensiveness of the list of criteria, and also on the presentation and/or wording of the criteria. Their responses were positive that the criteria were salient to structural frame and that no additional criteria were needed, indicating the comprehensiveness of the list. Moreover, the presentation and wording of the criteria were well understood. The only minor comment received related to the Likert scale used. The questionnaire was amended to ask respondents to rate the importance of SFPC, on a six point scale ranging from 0 "no importance" to 5 "extremely important." The amended questionnaire was reissued to these practitioners for further comments. The questionnaire was judged to be ready for administration to a wider sample.

Questionnaire Survey

A covering letter accompanying the questionnaire was written to describe the research aim and HCC (including illustrations of recent projects). Questionnaires were distributed to a selected sample of practitioners at managerial levels, including experienced clients, contractors, architects, engineers, and quantity surveyors, based on various databases. Appropriate databases were drawn upon to ensure that the respondents represented a stratified cross section of the stakeholders relevant to the research. Experienced clients included U.K. private and public clients, defined as those who regularly procure construction works from the industry. Private clients included developers, retailers and financial institu-

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Table 1. Questionnaire Distribution and Response

Respondent group	Number of questionnaires: Distributed	Returned	Response rate (%)
Client	79	7	8.9
Engineer	29	11	37.9
Architect	65	15	23.1
Quantity surveyor	6	3	50.0
Main contractor	96	16	16.7
Total	275	52	18.9

tions. Retailers and financial institutions were identified from the listing of Key British Enterprises (Dun and Bradstreet 1998). Developers were identified from the Estates Gazette (1999) and the Kompass (1999–2000). Public clients, i.e., local authorities or City Councils, were identified from the Municipal Year Book (Hill 1999). Contractors were identified from the listing of Key British Enterprises (Dun and Bradstreet 1998) representing the top U.K. contractors, the Kompass (1999–2000), and chartered building companies (CIOB 1998/1999). Architects were identified from the list of top U.K. architects (Knutt and Osborne 1998) and the RIBA Directory (RIBA 1998). The structural engineers, quantity surveyors, and a number of the architects and clients were selected from a privately held database of practitioners who had worked on completed HCC buildings and whom had also participated in U.K. government-funded research on best practice in concrete frame design and construction.

Additionally, some 27 members of the "Construct" Concrete Structures Group (an association of member companies dedicated to the task of improving the efficiency of building in situ concrete frames and associated structures) were invited to participate via e-mail. Generally, all respondents were well informed practitioners regarding various types of structural frame choices, the frame selection processes and HCC. Table 1 presents the number of questionnaires distributed and returned as well as their associated response rate for each group of respondents. Overall, 275 questionnaires were distributed and 52 completed, representing an 18.9% response rate. Although relatively modest in percentage terms, the completed questionnaires provided high quality data for subsequent analysis due to the respondents' extensive experience. Main contractors formed the largest group, followed by architects and engineers.

Application of Factor Analysis

Factor analysis is a statistical technique to describe a large set of variables by means of a smaller set of composite variables, called factors, hence aiding the interpretation of data. The main purpose is to determine the number of common factors that would satisfactorily produce the correlations among the criteria (Kim and Mueller 1978a). This technique allows for data reduction and provides a convenient means of exploring the interdependence of variables. This technique is appropriate for the research problem posed in this paper since the writers wished to explore the underlying dimensions behind SFPC, as well as interrelationships between the criteria. Ultimately, this should improve interpretation and understanding of the criteria for the benefits of practitioners in general and designers (i.e., engineers and architects) in particular.

The analysis was conducted using Statistical Package for the Social Sciences (*SPSS*) 11.0 for Windows. Several principal steps for this analysis are explained as follows.

1. Examining the sampling adequacy in order to ensure that the analysis is meaningful. One way to do this is by using Kaiser-Meyer-Olkin (KMO) measure, which is an index between 0 to 1. Small values for the KMO measure (i.e., below 0.5) indicate that a factor analysis of the variables may not be appropriate, since correlations between pairs of variables cannot be explained by the other variables (Norusis 1994, p. 52). This can further be confirmed by Bartlett's test of sphericity, which tests the null hypothesis that the correlation matrix is an identity matrix (i.e., there is no correlation between criteria) (Norusis 1994, p. 50). The value of the test statistic for sphericity is based on a chi-square transformation of the determinant of the correlation matrix.
2. Extracting the factors. Common factors were extracted using principal components analysis. The Kaiser's criterion, the most commonly used procedure to determine the number of initial factors to be extracted, stipulates that the number of factors determined was based on the criterion that the Eigen value for each factor should be greater than 1 (Kim and Mueller 1978b).
3. Rotating the factors. To achieve the simplest possible structure in order to obtain more interpretable factors/dimensions, promax oblique rotation with the power (*kappa*) valued at 4 was utilized. Oblique rotation (as opposed to orthogonal rotation) was utilized since it allows the presence of correlations between components/dimensions.

Structural Frame Performance Criteria

SFPC are those that can be used to measure the potential performance of structural frames. Performance was defined as the ability of the building to meet its specified requirements throughout its design life. This broad-based definition encompasses various aspects of the building and is not restricted to structural performance. To assess the structural frame during the early design stages as discussed in this paper, "potential performance" refers to the likely capability of each frame option to meet the needs of the building and its client. To compile these criteria, a review of building performance literature was conducted (see Table 2). Appropriate criteria were taken from various official indicators for performance and POEs of buildings. These are summarized in the following.

Key Performance Indicators

Key performance indicators (KPIs) were developed in response to a recommendation of the Egan report (1998), and were aimed at improving the performance of the U.K. construction industry based on measurement. Ten KPIs were produced as a set of benchmarks to measure performance of various parties involved in construction as a basis for comparison with the rest of the industry (KPI Working Group 2000). These were: construction time; construction cost; safety; productivity; profitability; time predictability (design and construction); cost predictability (design and construction); defects; client satisfaction—service; and client satisfaction—product.

Housing Quality Indicators

The Housing Corporation in collaboration with Building Research Establishment (BRE 2000a) established housing quality indica-

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Table 2. List of Sources of Structural Frame Performance Criteria

Criteria/indicators	Abbreviation	Source
Key performance indicators	KPIs	KPI Working Group (2000)
Housing quality indicators	HQIs	BRE (2000a)
Environmental performance indicators	EPIs	Sustainability Working Group (2001)
Sustainability indicators	SusInd	BRE (2000b)
Building research establishment environmental assessment method	BREEAM	BRE (2001)
Sustainable project appraisal routine	SPeAR	Arup (2003)
Environment key performance indicators	Environment KPIs	DTI et al. (2003)
Design quality indicators	DQIs	CIC (2002)
Postoccupancy review of buildings and their engineering	PROBE	Cohen et al. (2001)
Postoccupancy evaluation criteria classified into technical, functional, and behavioral	—	Preiser (1983, 1989, 1995)
Postoccupancy evaluation criteria classified into physical system, environmental quality, functional system, and behavior factors.	—	Carpenter and Oloufa (1995)
Postoccupancy evaluation of the Forrestal building	—	Sanders and Collins (1995)
Evaluating office environments using tenant organisation perceptions	—	Bottom et al. (1997)
Residential satisfaction in housing estates	—	Liu (1999)
Intelligent office building performance evaluation	—	Preiser and Schramm (2002)
Appraising the total performance of buildings	—	Douglas (1993/1994)
HCC criteria based on interview data analysed using cognitive mapping tool	—	Barrett (2001)
HCC criteria based on interviews	—	Glass (2002)

tors (HQIs), which provided a basis for a measurement and assessment tool designed to allow all potential or existing housing schemes to be evaluated on the basis of quality rather than simply of cost. Three key features of HQIs are location, design, and performance which produce ten "quality" indicators including: location; site—visual impact, layout, and landscaping; site—open space; site—routes and movement; unit—size; unit—layout; unit—noise, light, and services; unit—accessibility; unit—energy, green, and sustainability issues; and performance in use.

Environmental-Related and Sustainability Indicators

Environmental performance indicators (EPIs) for sustainable construction were developed under the Movement for Innovation (M4I) framework, in response to the Egan report (1998). The M4I Sustainability Working Group (2001) acknowledged that long-term sustainability requires an appropriate balance between social, economic, and environmental factors. The Working Group produced six EPIs, which were aimed at providing a simple, practical means of setting an appropriate number of quantifiable environmental targets for most building types to be used by all parties involved throughout project stages. These were: Operational carbon dioxide emission (kg CO_2/m^2/year); embodied carbon dioxide (kg CO_2/m^2); water [m^3/person (equivalent)/year]; waste in the construction process (m^3/100 m^2 floor area); biodiversity (measure being developed); and transport (measure being developed). Working within a similar framework, BRE (2000b) further developed these by providing a checklist questionnaire to operationalize the three "pillars" of sustainability (i.e., social, economic, and environmental).

The Building Research Establishment (BRE 2001) produced a tool for assessing and improving environmental performance of building called Building Research Establishment Environmental Assessment Method (BREEAM). The environmental implications of a project including (e.g., energy consumption, waste, and pollution) are evaluated by assigning points/scores to various statements in a checklist. Total scores are used to determine the EPI from 1 to 10 (the higher the better) and the BREEAM rating (pass, good, very good, and excellent).

Arup (2003) developed a tool to demonstrate the sustainability of a project, process, or product to be used either as a management information tool or as part of a design process, called the Sustainable Project Appraisal Routine (SPeAR). SPeAR focuses on the four elements of environmental protection, social equity, economic viability, and efficient use of natural resources, which are presented in the form of a four-quadrant model.

The Department of Trade and Industry, BRE, and Construction Industry Research and Information Association (CIRIA) (2003) recently developed Environment KPIs oriented towards assessing the environment impacts of construction process and product. These were: impact on the environment—product and construction process; energy use (designed)—product; energy use—construction process; mains water use (design)—product; mains water use—construction process; waste—construction process; commercial vehicle movements—construction process; impact on biodiversity—product and construction process; area of habitat created/retained—product; and whole life performance—product.

Design Quality Indicators

The Construction Industry Council (CIC 2002) established an assessment tool to evaluate the design quality of buildings, called design quality indicators (DQIs). These were developed to respond to the criticism that the KPIs focused only on the physical construction process, and therefore lacked consideration of the design of the product as experienced by the end-user (Gann et al. 2003). Gann et al. (2003) further argued that this lack of consideration of design would result in unattractive and boring buildings and therefore did not result in added value to the stakeholders. CIC formatted a set of DQIs in a questionnaire comprising 97 indicators categorized under three main headings, i.e., "impact," "build quality," and "functionality." The web site of CIC (2003) defined these measures as follows:

- "Impact refers to the building's ability to create a sense of place, and to have a positive effect on the local community and environment. It also encompasses the wider effect the design may have on the arts of building and architecture." Impact includes indicators under four sub-headings including charac-

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ter and innovation, form and materials, internal environment, urban and social integration.

- "Build quality relates to the engineering performance of a building, which includes structural stability and the integration and robustness of the systems, finishes and fittings." Build quality concentrates on performance, engineering, and construction.
- "Functionality is concerned with the arrangement, quality and inter-relationship of space, and the way in which the building is designed to be useful." Functionality focuses on use, access, and space.

Scores attributed to the indicators are aggregated by considering the relative importance of the subheadings. The final results are presented in a spider chart, showing the performance of each subheading. This assessment can be conducted at any stage throughout a building's life, and is designed principally as a tool for learning about design quality through stakeholder debates, which provide a basis for continuous improvement (Gann et al. 2003).

Building Performance and Postoccupancy Evaluation Criteria

In addition to the main studies above, criteria were sought from various POEs of buildings. Most notably, the postoccupancy review of buildings and their engineering (PROBE) aimed to provide feedback to building designers, clients, and occupiers with technical and energy performance of buildings as well as occupant satisfaction (Cohen et al. 2001). Preiser (1983, 1989, 1995) classified building evaluation into: technical (health/safety/security); functionality/efficiency; and behavioral (social/psychological/cultural satisfaction). Carpenter and Oloufa (1995) classified performance criteria into four categories, i.e., physical system, environmental quality, functional system, and behavioral factors. Sanders and Collins (1995) conducted a POE of the Forrestal building, which employed physical measurements of lighting and other environmental conditions, and a questionnaire asking occupants' opinions on working environments. Bottom et al. (1997) reported the results of a standardized POE questionnaire survey of tenant organizations occupying office buildings in London. Liu (1999) applied a factor analysis technique to POE data from several residential buildings. Nine factors were identified, namely: Management and maintenance of the estate; lighting and ventilation; convenience of location; appearance of building; surroundings; spatial movement; fire services installation; appropriateness of site including privacy; and building materials used. Preiser and Schramm (2002) developed a POE process model and listed performance criteria in order of priority as: Health; safety; security; function; efficiency; work flow; psychological; social; and cultural performance.

Douglas (1993/1994) discussed the holistic appraisal of building performance which includes preconstruction (e.g., value management), during construction and post construction (e.g., POE). He then proposed ten principal criteria for a macrolevel evaluation of nonresidential buildings. These were: Investment returns; energy efficiency; space utility; cost-in-use; restoration costs; code compliance; building integrity; internal environment; quality; and durability.

HCC-Specific Criteria

Based on interview data analyzed using a cognitive mapping tool, Barrett (2001) identified salient criteria for contractors in their choice and use of HCC (in descending order of support): aesthetics; function; speed; responsiveness; safety; integration; buildability; and confidence. Aesthetics and function are about the quality of the "product" and are amongst the strongest points for adoption of HCC technology, whereas the remaining criteria deal with the "process" (Goodchild 2001). From interviews with thirteen experienced practitioners, Glass (2002) identified HCC performance indicators which were classified 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. Lesser importance indicators comprised buildability, environmental, finish, quality, site conditions, structure, market conditions, and safety.

The inclusion of the HCC-specific criteria to the list was not intended to introduce biases toward the use of HCC, but to ensure comprehensiveness of the list. Additionally, their inclusion was to "factor" criteria from high quality solutions such as HCC.

Summary

Based on the range of criteria reviewed previously, all the potential indicators/criteria were evaluated meticulously for their relevance to structural frames. Overall, 31 relevant criteria were selected which represent a synthesis of the many criteria identified from the literature. These were classified approximately into five main aspects including impact, performance, use, form and materials, and process. Table 3 depicts a matrix indicating the relationships between these criteria and their sources. The pilot survey confirmed that the criteria were salient to structural frame selection process and that no additional criteria were needed, indicating the comprehensiveness of the list.

The criteria have two important characteristics. First, SFPC are relevant for evaluating performance of both the physical construction process and end product (i.e., the building). Secondly, SFPC address both hard and soft issues. The *hard* criteria include issues such as cost and speed of construction, which are quantifiable in nature allowing a more objective assessment. In contrast, the *soft* criteria include more qualitative factors relating to individual perceptions such as confidence and satisfaction with the finished product, which are more subjective in nature.

Characteristics of the Respondents

Characteristics of the respondents are described into two main sub-sections, respondents' background and their awareness and experience of HCC, as follows.

Respondent and Company Background

Figs. 1 and 2 present histograms showing the length, in terms of number of years, for which the respondents had worked in the construction industry and in their present companies. The average length of working in the industry was 28 years, whereas the average length of working in the present companies was 14 years. This suggests that the respondents are very experienced experts in their fields whose opinions ensure high quality and valid data.

Generally, the company size varied widely, from large to microcompanies (i.e., employing 5 or less). The largest companies employed up to 35,000 people and had annual turnovers of over £500 millions, whereas the smallest companies employed only 4 or 5 people with annual turnovers of less than £1 million.

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Table 3. Structural Frame Performance Criteria and their Sources

Indicators	KPI	HQI	EPI	SusInd	BREEAM	SPeAR	Environment KPI	DQI	PROBE	Preiser (1983, 1989, 1995)	Carpenter and Oloufa (1995)	Sanders and Collins (1995)	Bottom et al. (1997)	Liu (1999)	Preiser and Schramm (2002)	Douglas (1993/ 1994)	Barrett (2001)	Glass (2002)
Impact																		
The building reinforces the image of the occupier's organization								×		×								
The building reflects the status of the occupier										×	×							
The building overall meets perceived needs									×	×								
The building enhances the team/client's confidence (in the selected structural frame)																	×	
The building provides best value																		×
The client is satisfied with the finished product	×																	
Performance																		
The frame is structurally efficient								×						×				
The layout, structure and engineering systems are well integrated								×						×				×
The building is designed for demolition and recyclability				×	×		×	×										
Use																		
The layout and size work well		×						×		×	×	×	×	×	×	×		
The circulation works well		×						×		×	×		×	×	×	×		
The building is adaptable to changing needs								×			×							
The building has sufficient floor to ceiling clear height										×			×	×				
The building provides appropriate lettable area/spans																		×
Form and Materials																		
The form is well conceived								×				×		×				
The color and texture of materials enhance enjoyment of the building								×				×		×				×
The finishes are durable and maintainable		×						×			×		×	×				×
The quality and presentation of finishes are good													×					
The building overall looks durable																×		
The form and materials optimize the use of thermal mass							×										×	×

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Table 3. (*Continued.*)

Indicators	KPI	HQI	EPI	SusInd	BREEAM	SPeAR	Environment KPI	DQI	PROBE	Preiser (1983, 1989, 1995)	Carpenter and Oloufa (1995)	Sanders and Collins (1995)	Bottom et al. (1997)	Liu (1999)	Preiser and Schramm (2002)	Douglas (1993/ 1994)	Barrett (2001)	Glass (2002)
Process																		
The building can be quickly constructed	×																×	×
The design costs can be minimized																		×
The construction costs can be minimized	×																	×
The facility management (i.e., operation and maintenance replacement) costs can be minimized		×					×	×								×		
The disposal (i.e., demolition and site clearance) costs can be minimized				×	×		×	×										
The building minimizes environmental impacts (in terms of energy/resource consumptions and waste).		×	×	×	×	×	×	×							×	×	×	×
The building has been designed so it can be safety constructed	×							×									×	×
The building is perceived to be simple to build																	×	×
The connections between components are well designed and buildable																	×	×
The tolerances of the components are realistic																	×	×
The overall risk is perceived to be low																	×	×

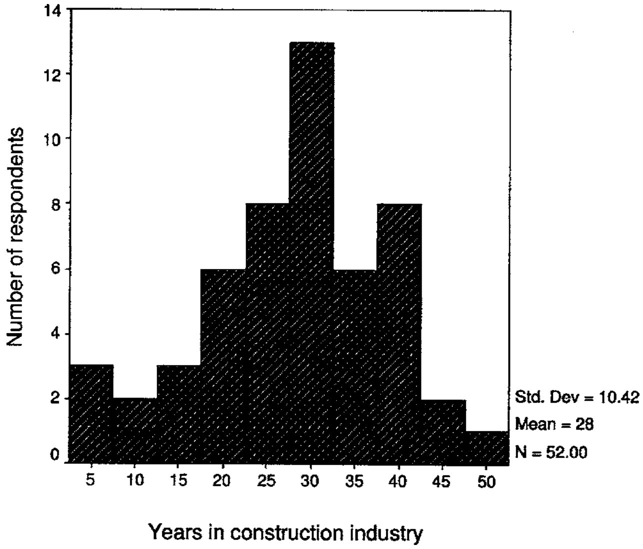

Fig. 1. Length of time respondents had spent in the construction industry

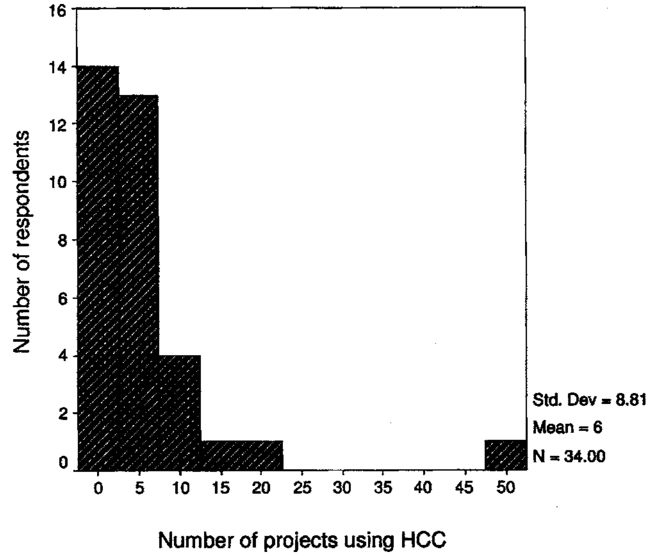

Fig. 3. Number of projects using HCC

Respondent Awareness and Experience of HCC

Since HCC is underutilized, and hence considered a technological innovation for many construction firms, it was important to ask respondents to assess their own companies' receptiveness toward technological innovation. Their assessment was made in relative comparison with other companies in similar field and size, as suggested by Toole (1994). Generally, they perceived their companies to be receptive toward new technology as almost all (96.2%) indicated that their company adopted new technology at least at the same time as others. Interestingly, more than half (51.9%) indicated their companies as leading adopters, with almost a quarter (23.1%) claiming confidently that their companies were the first adopters. Few regarded their company as unreceptive toward new technology. These findings highlighted the apparent competitive climate in the construction industry, as companies need to adopt new technology to be able to compete. The sampling method might also have influenced these findings since the selected companies represent those leading practitioners in their fields.

Almost all respondents (82.7%) were aware of HCC, but not all of them (69.2%) had used it in their projects. About 10% (9.6%) had used HCC frequently in their projects. If they had used HCC, the average number of projects using this frame was six (refer to Fig. 3). One specialist concrete frame contractor suggested that he had been involved in fifty HCC projects.

For those that had used HCC, further exploration of reasons for adopting this frame should reveal the advantages of its utilization, as presented in Fig. 4. These advantages should provide good reasons to promote the wider take up of HCC. Most (77.1%) agreed that the use of HCC helped to deliver the project program, hence speed is considered its main advantage. About half (48.6%) suggested that HCC delivered better quality, particularly due to off-site prefabrication of the precast components. More than one-third (37.1%) utilized HCC to keep projects under or on budget. It is worth noting that enhancing client satisfaction was the lowest voted by "only" 31.4 percent. Some respondents (22.9%) stated other reasons, such as buildability, flexibility, cost effectiveness, quality, health, and safety.

Clearly, to further realize the benefits of using HCC, assessment criteria have to be determined and evaluated, which could also be used to objectively compare performance against alterna-

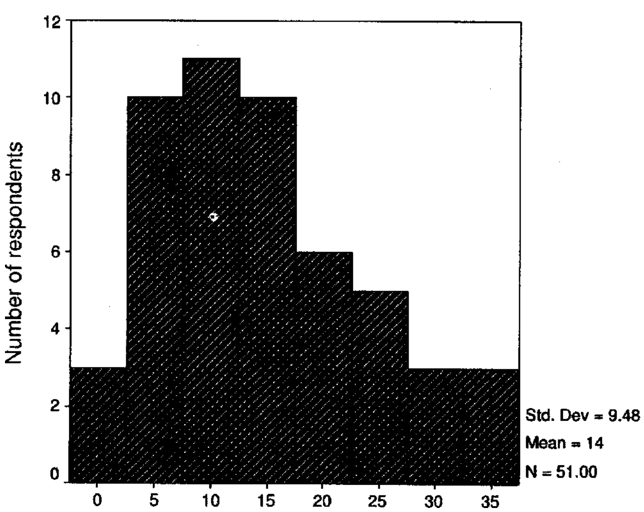

Fig. 2. Length of time respondents had spent in their present companies

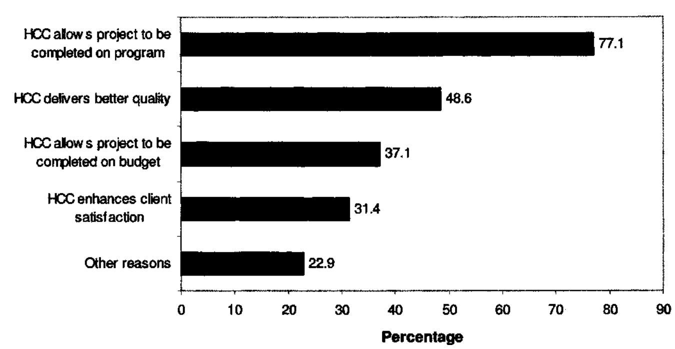

Fig. 4. Reasons for using HCC

Table 4. Summarized Results of Factor Analysis

Performance criteria	Factor loading	Variance explained (%)
Factor 1: Physical form and space		36.761
The layout, structure and engineering systems are well integrated	0.747	
The layout and size work well	0.770	
The circulation works well	0.804	
The building has sufficient floor to ceiling clear height	0.796	
The building provides appropriate lettable area/spans	0.747	
The form is well conceived	0.796	
Factor 2: Construction process		8.194
The frame is structurally efficient	0.678	
The building can be quickly constructed	0.787	
The construction costs can be minimized	0.695	
The building has been designed so it can be safety constructed	0.763	
The overall risk is perceived to be low	0.697	
Factor 3: Long-term sustainability		7.153
The building is designed for demolition and recyclability	0.629	
The building is adaptable to changing needs	0.714	
The finishes are durable and maintainable	0.686	
The form and materials optimize the use of thermal mass	0.564	
The facility management (i.e., operation and maintenance replacement) costs can be minimized	0.699	
The disposal (i.e., demolition and site clearance) costs can be minimized	0.757	
The building minimizes environmental impacts (in terms of energy/resource consumptions and waste)	0.777	
Factor 4: Establishing confidence		6.038
The building enhances the team/client's confidence (in the selected structural frame)	0.624	
The design costs can be minimized	0.593	
The building is perceived to be simple to build	0.713	
Factor 5: Building impact		5.318
The building reinforces the image of the occupier's organization	0.900	
The building reflects the status of the occupier	0.880	
The building overall meets perceived needs	0.558	
Factor 6: Physical appearance		3.719
The color and texture of materials enhance enjoyment of the building	0.590	
The quality and presentation of finishes are good	0.706	
The building overall looks durable	0.637	
The connections between components are well designed and buildable	0.742	
The tolerances of the components are realistic	0.747	
Factor 7: Client satisfaction		3.428
The building provides best value	0.766	
The client is satisfied with the finished product	0.643	
	Total	70.611

tives, such as in situ and steel. For evaluation purposes, the criteria were subjected to factor analysis, the results of which are presented in the following section.

Factor Analysis Results and Discussions

Initial investigation indicated that factor analysis could be meaningfully applied in this research [the KMO was 0.674 and the chi-square test was significant ($p<0.0005$)]. The result of the analysis is presented in Table 4. Seven factors (also called dimensions, the meaning of which is more appropriate for a discussion of performance aspects in this paper) of SFPC were resulted directly from this analysis. This finding suggests that SFPC could be interpreted using seven underlying performance dimensions. These dimensions explained 71% of the variation in the importance levels of the criteria. Specifically, these seven dimensions accounted for 36.8, 8.2, 7.2, 6.0, 5.3, 3.7, and 3.4% of the variance, respectively. High intercorrelations between the criteria within one dimension indicate that achieving the performance tar-

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get of one criterion should also achieve the target for the other criteria due to the same level of importance. This is based on the assumption that to achieve optimum performance for a particular criteria, levels of performance should be in accord with levels of importance (Martilla and James 1977; Soetanto et al. 2001). Description of the seven dimensions and their constituent criteria is presented here.

Factor 1: Physical Form and Space

The first dimension concerns layout and space for both engineering systems and potential occupiers, which could be interpreted as the "physical form and space" dimension. The choice of structural frame may influence the quality and "quantity" of physical space available, which in turn impact on the productivity and comfort of potential occupiers. HCC is regarded as providing appropriate lettable area/spans and sufficient floor to ceiling clear height due to the appropriate selection of precast components and their combination with in situ components. HCC also provides great freedom and flexibility, in terms of moldability of concrete (Freedman 2001) for designers to design a building space with an excellent blend of balanced layout, size, circulation, well-conceived form, and well-integrated engineering systems. Here, rigorous advanced planning and detailed design, as well as good communication between members of project team are essential for the success of HCC projects.

Factor 2: Construction Process

The second dimension concerns structural efficiency, time and cost minimization, construction safety and risk, which are related to "construction process." Generally, a structurally efficient building frame will shorten program, minimize cost, reduce the occurrence of accidents, and hence lower the overall risk. This is also connected to off-site fabrication of precast components, which many believe speeds up the construction process and brings a safer site. The use of HCC was perceived as not minimizing cost (Goodchild 2001), hence cost does not provide advantage for its adoption. However, Gibb (1999) claimed that the use of prefabrication components reduced overall cost due to reduction in project time, enabling earlier income generation for client and reducing the extent of site activities. Nevertheless, it will incur extra costs due to transportation, craneage, and factory overheads. Gibb further suggested that the main cause of these extra costs was the failure to assess all the costs involved in traditional construction (as a benchmark or reference for comparison). Arditi et al. (2000) commented that delays in production schedules due to lack of expertise and communication during design stage, marginalized the potential cost saving benefits of precast concrete. Overall, HCC contributes positively to construction process.

Factor 3: Long-Term Sustainability

The third dimension focuses on "long-term sustainability" including criteria such as: recyclability (when demolished); adaptability; durable and maintainable finishes; the use of thermal mass; minimization of facility management; disposal costs; and environmental impacts. Based on interviews with major industry players, Glass and Baiche (2001) found that thermal mass (described as the energy storage capacity of the concrete as a means of stabilizing internal temperatures and offsetting both internal and external heat gains) was perceived as one of the main benefits of HCC. Although this is a common feature of all heavyweight materials, interviewees explained that the use of high quality architectural concrete as exposed soffit or permanent formwork units in the HCC structure enabled designers to easily and attractively incorporate thermal mass benefits into the building.

With increasing awareness of unprecedented global warming and scarcity of natural resources, sustainable construction has become important within the performance improvement agenda, as evidenced by the release of various sustainability related indicators (e.g., BRE 2000b; Sustainability Working Group 2001; DTI et al. 2003). The use of HCC is particularly advantageous in this respect since precast components can potentially be reused. Further, due to the controlled factory environment, smooth and durable finishes can be obtained, thus reducing the need for costly finishing works. Ultimately, this will also reduce facilities management (i.e., operation and maintenance) and disposal costs, as well as minimizing environmental impacts in terms of energy/resource consumption and waste. Here, the project team should be made aware of what HCC can offer, thereby maximizing the benefits from using HCC and enhancing its adoption within the industry.

Factor 4: Establishing Confidence

Project team/client confidence in the selected structural frame was linked to minimization of design costs and simplicity to build. Confidence to use a different (i.e. nontraditional) structural frame, such as HCC, is essential for its adoption. Therefore, designers and precasters play a key role in creating higher confidence. This dimension suggests that to secure confidence, they should demonstrate the simplicity of the structural frame and form to be built, and that the selected structural frame will minimize design cost. This dimension is therefore related to "establishing confidence."

Barrett (2001) argued that today's lack of confidence in using HCC is a result of past experiences where there was limited contribution of concrete industry in the early design stages, lack of standards to refer to, and doubt toward structural integrity of composite structures which was exacerbated by unsophisticated image of the industry. To boost confidence and enhance the likelihood of adoption, the industry should demonstrate expertise and provide successful past experiences, by for example using a project team, which has been successful in using HCC in their previous projects (Barrett 2001).

Factor 5: Building Impact

It is also surprising that "building to reflect the image and status of the occupiers" criteria are strongly related to "building to meet perceived needs." This reflects the tendency to link perceived needs with the design flair/aesthetics of a building. This dimension is then called "building impact," which concerns how the building (i.e., end-product) derives (positive/negative) "soft and intangible" impacts on its surroundings. This suggests that at present, the actual needs of occupiers/clients are perceived to be shifting to higher level of needs, which is analogous to Maslow's hierarchy of needs (see Preiser 1983). This can be demonstrated since most current of HCC is for high profile building projects, such as Toyota U.K. Headquarters. Here, such clients wish their buildings to reflect the company's high image and status. The off-site fabrication of precast components allows high quality finishes and various forms to be produced, which enhance building aesthetics and create a positive impact on its surroundings. Goodchild (2001) suggested that aesthetics was one of the strongest driving forces for the use of HCC. Apparently, this opportunity

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should be explored and this dimension used to demonstrate potential benefits derived from using HCC during the conceptual design of a building.

Factor 6: Physical Appearance

This sixth dimension concerns "physical appearance" of the building including criteria such as color and texture, quality and presentation of finishes, overall durability of building, as well as connections and tolerances of components. This dimension overlaps somewhat with the *building impact* dimension, although the focus here is on micro/detailed level of assessment. Technological innovations in the precast industry have made it possible to produce precast components which meet the needs of designers to create positive impacts on the environment surrounding the building, by using multitude of different forms, colors, surface finishes, and architectural designs (Freedman 2001). However, the off-site manufacture of precast components may pose erection problems due to difficult connections and strict tolerance. These are exacerbated by the lack of expertise in HCC design, provoking conflicts between designers and precasters (RPEG 2001). Nevertheless, these can be eliminated by advance planning and careful detailed design as well as better communication between parties involved.

Factor 7: Client Satisfaction

The final dimension comprises criteria on the "building providing best value" and "client satisfaction with the finished product," which are considered as the penultimate aim of any building project and therefore named "client satisfaction." It is essential that the selected structural frame solution delivers best value to the client. Goodchild (2001) proposed the use of Value Management techniques to evaluate alternatives and select the best value solution based on predetermined criteria. Here, the client should define what value means to them by ascertaining the relative importance of these criteria, and then the best value solution is selected by matching the client's assessment and the performance of different alternatives. This will deliver best value and satisfaction to the client. HCC provides a superb finished product, in terms of aesthetics and function, as demonstrated by buildings using precast components (Freedman 2001; Goodchild 2001). Essentially, best value buildings overall are more likely to enhance client satisfaction.

Implications and Practical Application of Structural Frame Performance Dimensions

The utilization of SFPC and dimensions focuses on early project stages (i.e., conceptual design/options study sessions), during which the project team (commonly including client and/or client's agent, architect, structural engineer, and potential contractors/subcontractors, e.g., precaster) should discuss and decide on the appropriate structural frame solution from a range of alternatives for their project. Traditionally, it would appear that the appropriate solution is selected based on cost, time, and quality criteria. Although these are commonly regarded as key performance criteria, their utilization is probably too simplistic in the light of various performance issues (e.g., environmental impact and aesthetics), which are becoming more important in the present and future construction. Moreover, inputs from all members of the project team are essential for smooth delivery and for judging the overall success of the project. Their criteria for selecting a structural frame solution are likely to be broader than simply cost, time, and quality. A comprehensive and authoritative list of criteria is highly important for them to be able to deliver best solution to the satisfaction of client. Indeed, this is not to suggest replacing traditional criteria with the seven dimensions, but these traditional criteria have been factored within the SFPC and hence within the seven dimensions.

The seven dimensions of SFPC should assist the project team in their decision making process at the conceptual design stage by providing a simple list of performance dimensions to be considered. The discussion to select an appropriate structural frame should occur at a project meeting where team members are allowed to communicate, discuss, and rethink their ideas. Hence, the dimensions provide a reference for this exercise and specifically, a basis for assessing (i.e., discussing) advantages and disadvantages of structural frame options. Here, it is crucial the team members adopt a proactive and cooperative attitude in dealing with other members and willingly appreciate their ideas, without the presence of a hidden agenda, so that the optimum solution can be achieved to the benefit of all project stakeholders, especially the client.

Some may regard this assessment as subjective and therefore, lacking precise measurements for consistent comparison for an engineering decision. However, the aim is to provide an authoritative list of SFPC to assess structural frame alternatives and hence facilitate a more objective and transparent decision-making process where the potential of all alternatives could be realized and assessed fairly. This exercise would also capture the potential value of structural frames, and shift the perspective somewhat from over-reliance on cost and speed as the only parameters for selecting an appropriate structural frame. Some aspects of structural frame performance are "less tangible" and wholly determined by the individual nature of the project in hand, so cannot always be measured objectively. However, this less tangible nature should not be a legitimate reason for not considering these aspects within the decision making process as these aspects are often critical to achieving higher value. Instead of avoiding the assessment of these less tangible and subjective aspects, the measurement of intangible aspects should constitute an invitation to dialogue (Sveiby 1997 c.f. Gann et al. 2003). SFPC should represent salient issues to extend the dialogue into a more structured and constructive discussion among relevant members of project team. Here, a methodology is required to support the discussion. The methodology assesses structural frame alternatives using two measures, importance (I) and performance (P). Importance (I) indicates the value or weight for each criterion in relation to: client and project objectives; and influence on the decision-making process for structural frame selection. The value of P indicates how well a particular structural frame scores against a certain aspect of performance. The values of I and P can then be used to calculate a Performance weighted score (PWS), created to integrate the importance values into the assessment, allowing those criteria considered more important to be prioritized accordingly. The PWS for each dimension is the average PWS of all criteria included in that dimension. The actual "scores" derived from the assessment themselves are not critical, as the framework essentially serves as a guide to discuss various performance issues and integrate the various views of stakeholders. This methodology and its validity are the subject of current research. This work will embed this methodology within a decision support tool, for example in the form of virtual reality software which allows

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SFPC and dimensions to be discussed, visually assessed, and simulated during the frame choice meeting.

Conclusion

Promoting the wider take-up of a high quality structural frame such as HCC, requires criteria to assess the relative advantages of this frame against alternatives to be determined, defined, and then evaluated. This research has compiled a list of SFPC based on a comprehensive review of literature in the domain of building performance including various official indicators of performance and postoccupancy evaluation. To obtain the perceived importance of the criteria, a questionnaire was designed and distributed to a selected sample of experienced practitioners including clients, engineers, architects, quantity surveyors, and main contractors.

Background information revealed that most respondents were aware of HCC although not all of them had used it in their projects. The most common reason for the use of HCC was thought to be its speed of construction. Interestingly, client satisfaction was considered to be the least important reason from the list provided. Generally, the practitioners perceived "speed" as the key advantage of HCC, although there are may more advantages, which could be gained. This paper demonstrates other advantages of HCC by compiling and evaluating criteria, which include both hard and soft (i.e., quantifiable and nonquantifiable) issues.

Factor analysis of the data yielded seven dimensions of SFPC. These were interpreted as physical form and space, construction process, long-term sustainability, establishing confidence, building impact, physical appearance, and client satisfaction. These could be used to assist the project team in their decision making process during conceptual design stage by providing a simple list of dimensions to be considered. Although these SFPC and dimensions were developed to realize the benefits of using HCC, they are transferable to comparisons that do not include HCC, but that aim to obtain a high quality structural frame solutions based on more than crude time and cost comparisons. Future research will develop decision making tools based on IT systems to assist team members to evaluate and compare the performance of various structural frame alternatives using the criteria and dimensions derived.

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