A 'HYBRID' MULTI-STOREY BUILDING – MEETING DESIGN CRITERIA IN A COST-EFFECTIVE WAY

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ABSTRACT

New, innovative timber structural components and systems now offer alternative building-solutions to traditional concrete and steel structural systems. A detailed design study on a proposed new building in Christchurch demonstrates the relative merits of each material in a multi-storey commercial setting. Defined criteria give rise to an *Optimal 'Hybrid'* Design – using '*the right material for the right application'* – where timber components and systems are selected for many structural elements and compares this to an *All Timber* design and a ductile structural system. The study demonstrates the financial implications on the overall construction cost of selecting different materials for different purposes and the cost premium of a 'damage-resistant' building over conventional Ductility 3 code requirements.

The study shows that in a commercial context, there is no single structural material – either timber, concrete or steel - that is appropriate in all circumstances and material selection is often subjective.

The study was carried out by the University of Canterbury and Irving Smith Jack Architects Ltd. on behalf of the New Zealand Government's Ministry of Primary Industries (MPI).

INTRODUCTION

The final design of a large-scale commercial building is the product of an often long and complex assessment process involving many significant choices and decisions. New, innovative timber structural components and systems now offer alternative building-solutions – that is, '*options'* - to traditional concrete and steel structural systems. Demonstrating the relative merits of each material in a commercial building, this article summarises the findings of a detailed design study on a proposed new building in Central Christchurch. The designs arise from defined selection criteria to produce an *Optimum 'Hybrid'* Design – using '*the right material for the right application'* - for a proposed multi-storey commercial development as part of the Christchurch 're-build'. The '*Hybrid*' design is compared to an *All Timber* design and a more conventional ductile structural system.

The overall construction cost of a new building is almost always an important selection criterion. Whilst this study considers cost as only one of ten equally-weighted selection criteria, it demonstrates the financial implications on the overall construction cost of selecting different materials for different purposes.

The study shows that in a commercial context, there is no single structural material – either timber, concrete or steel - that is appropriate in all circumstances. However, the study also highlights that timber elements and systems are able to fulfil all the specific selection criteria for many structural elements in a multi-storey buildings including being cost competitive.

The study also indicates that material selection is often subjective – determined by the specific selection criteria imposed, and the perceived relative importance of those criteria. It is evident that there is not a single universally superior material for all applications and, conversely, there is no single material that is generally inferior. Hence, the *Optimum Hybrid Design* combines structural components and systems manufactured from different materials.

For the defined selection criteria, for the majority of structural elements, there is often little difference between the materials in terms of overall suitability and it is apparent that a slight shift in selection criteria would most likely produce different results and, consequently, a different combination of 'optimum' materials. It must be carefully noted that the selections made for the Hereford Street building are based on a set of criteria that may not be directly applicable to another building.

The study was carried out by the University of Canterbury (UC) on behalf of the New Zealand Government's Ministry of Primary Industries (MPI). Irving Smith Jack Architects Ltd. (ISJ) was engaged to explore and report on alternative design approaches, working closely with Aurecon NZ Ltd. structural engineers to produce concept drawings. These drawings were the basis for a preliminary cost estimate by quantity surveyors Rider Levett Bucknall (RLB).

UC has presented MPI with a detailed report compiled by ISJ Architects [1] – the full report is available at http://www.civil.canterbury.ac.nz/structeng/timberpubs.asp

This article presents only a summary of the findings from that report.

THE CONCEPT OF A 'HYBRID' BUILDING

Over the last ten years, there have been numerous studies to compare various aspects of buildings constructed from different materials; many have made comparisons between a building where the main construction material has been either timber, or concrete, or steel. For instance, studies have used full (or partial) life cycle assessment (LCA) to compare environmental impacts of different building materials (for a synthesis of recent LCA research, see Sathre, R. and O'Connor, J., 2008). Few studies have investigated multi-storey, commercial buildings – fewer still have presented cost comparisons. The research report by John (2011), investigated the cost, time and environmental impacts of the construction of the new Nelson and Marlborough Institute of Technology (NMIT) Arts and Media complex in Nelson, an 'as-built' multi-storey building where the main structural components were made of timber – laminated veneer lumber (LVL) – and compared this to similar building models which used either concrete or steel for the main structural components. A predominance of one structural material, often leads to the building being labelled as such – for instance, the NMIT Arts and Media building is most often referred to as a 'Timber' building, although it includes a number of other structural materials.

However, in the 'real world', every building is constructed from a variety of materials – it is the relative proportion (usually measured by mass) of each material that varies. The cost comparison on the NMIT building pointed to the most cost-effective design being one which would combine different structural materials - termed a 'hybrid' building.

In such a building, the structural system's major components – for example, shear walls, columns and beams, etc. – may be made from different materials – broadly, using *the right material for the right application*.

THE CASE STUDY BUILDING - HEREFORD STREET, CHRISTCHURCH

A central-city building at 190 Hereford Street, Christchurch was irreparably damaged in the earthquakes of 2011 and was subsequently demolished. Designing a four storey structure to replace this building has provided an opportunity to rigorously assess how a timber structural system compares in a multi-storey, commercial development with more traditional concrete and steel structural systems.

The proposed building (gross floor area 2,400 m^2), required to offer maximum flexibility to accommodate a variety of potential commercial uses, was designed in late 2011 within the known constraints of the site and Christchurch City Council rules and regulations.* Of over-riding importance was that the building must provide *damage-resistant* structural design technology, aimed at minimising any future earthquake damage (with the building able to return to its original position

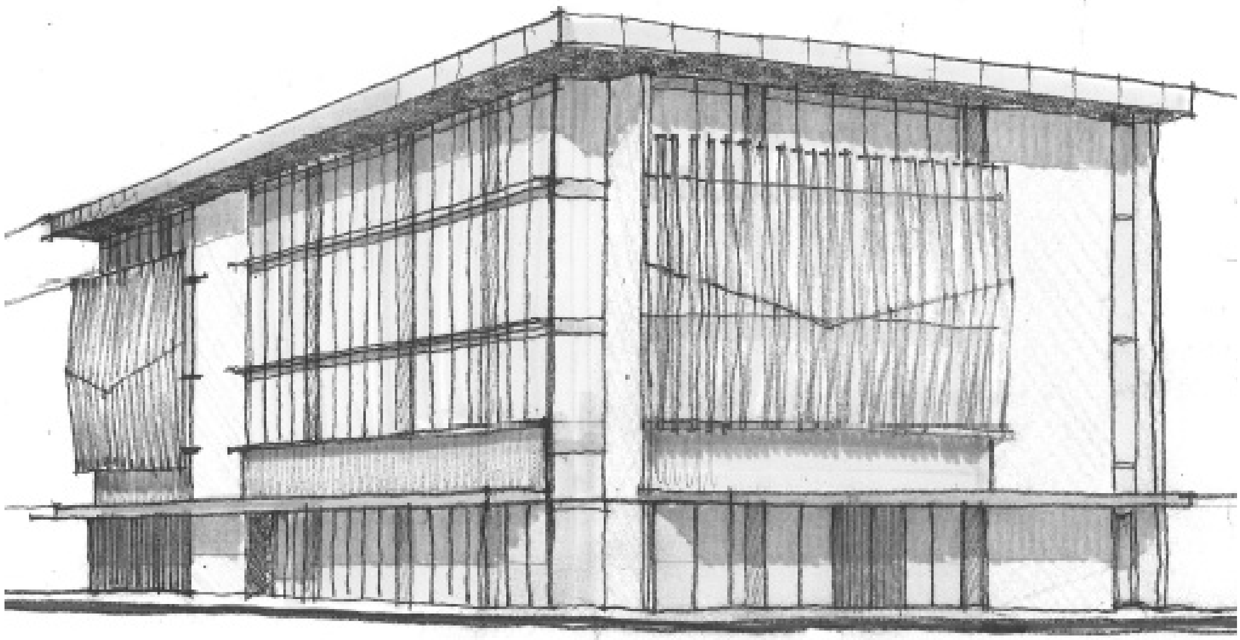

Figure 1. Architect's concept sketch of the proposed building at 190 Hereford Street, Christchurch. Design by Irving Smith Jack Architects, Nelson.

*This report was complied under the Christchurch City Council (CCC) draft Recovery Plan (Central City Plan) for the Central Business District (CBD) as it existed through the later half of 2011 and early into 2012. In June 2012, the CCC released the final Christchurch Central Recovery Plan (http://ccdu.govt.nz/the-plan).

without permanent offset or tilt), as well as offering environmentally sustainable features. Damage-resistant design means that the building should be fully serviceable after a major seismic event (Richter 7.0 – 7.9) and be quickly and safely reoccupied, minimising the time during which commercial tenants may be prevented from reoccupying a building. An architect's concept sketch of the proposed building is shown in Figure 1.

OPTIMISATION STUDY - RESEARCH METHODOLOGY

A general design brief (project, description and objectives) was provided by the site owner. Through an iterative design process, combinations of timber, concrete and steel structural elements were considered and evaluated. In general terms, each of these systems incorporates the objectives within the design parameters taking into account the various inherent characteristics and capabilities associated with each material.

ISJ made an objective assessment of each system for the Hereford Street building based on documented evidence, detailed analysis and the collective experience of the whole design team, to discover the optimum building material for each particular elemental application in view of the overall structural solution. Aurecon NZ provided structural engineering expertise at each design stage and ISJ and Aurecon together agreed upon the *Optimum 'Hybrid'* design (and later on the *All Timber* design and a conventional ductile structural system). RLB used concept drawings to provide preliminary estimates of materials and costs for all designs.

For the purpose of comparing structural elements, the study focused on the structure above ground level, with only commentary on alternative foundation systems for this site. Whatever foundation option is used, it was assumed that the ground floor would consist of a reinforced concrete slab.

The building design has six main structural elements, each with a number of potential options, as shown below:

PURLINS

- Laminated veneer lumber (LVL)
- Glulam
- Steel (cold rolled C-section)
- I Joist ("Hyjoist")
- Cross laminated timber (CLT) panels

RAFTERS

- Bolted LVL
- Bolted glulam
- Bolted steel

UPPER FLOORS

- Cross laminated timber (CLT)
- Stress-skin ("Potius" or CLT) timber floor system
- Flat slab / Unispan precast concrete with concrete topping
- Interspan / Stahlton precast concrete with permanent timber formwork and concrete topping
- Metal deck with reinforced concrete topping

STRUCTURAL FRAME (COLUMNS AND FLOOR BEAMS)

- Bolted LVL
- Bolted glulam
- Bolted steel
- Precast reinforced concrete

SHEAR WALLS

- Post-tensioned CLT
- Post-tensioned LVL
- Post-tensioned pre-cast concrete (PRESS)
- Reinforced in-situ concrete
- Reinforced concrete masonry
- Post-tensioned steel K-brace

FOUNDATION SYSTEMS

- Screw piles
- In-situ bored piles
- Continuous flight auger (CFA) piles
- Raft slab (over geo grid reinforced hard-fill)

Each option, for each element was evaluated in relation to the proposed alternatives. After collating this information, the architects evaluated the characteristics, advantages and disadvantages of each option to compare one with another in respect of the following criteria:

- Cost — Overall cost of production, delivery and erection.
- Seismic performance — Ability to meet specified levels of seismic resistance.
- Weight — Load imposed on superstructure and substructure.
- Bulk / size — Dimensional characteristics of members.
- Acoustic performance — Resistance to transfer of sound.
- Fire resistance — Inherent fire resistant characteristics.
- Environmental sustainability — Embodied energy, carbon footprint, GWP, etc.
- Speed of construction — Time required for erection / installation.
- Durability — Ability to meet building code durability requirements.
- Neighbourhood impacts — Impact on neighbourhood / public during construction.

The structural element comparison (Table 1) summarises results, with scores for each criterion ranging from 0 (uneconomical / low / poor) to 2 (economical / good). All materials were given the same score (1) where a particular criterion was not an important consideration. No weighting was added to scores to account for any criteria being more/less important or relevant than others. It is conceivable that for a different project where emphasis may be placed on different or particular criteria, the resultant score, and hence the material selection, may differ. Hence, it should be noted that results from this optimisation study are specific to the Hereford Street project and may not necessarily be applicable to any other project.

THE OPTIMUM 'HYBRID' DESIGN

Table 1 presents the cumulative scores for each structural component – for most components, the highest score leads to selection of that component or system in the *Optimum 'Hybrid'* damage-resistant design, comprising a combination of materials, as shown in Table 2.

Table 2. Structural components in the *Optimum 'Hybrid'* damage-resistant design for 190 Hereford Street.

Structural component	Selected material / system
Purlins	Steel DHS300/15
Rafters	Steel 310UB40.4
Upper floors	CLT 320mm Stress-skin system
Columns	400 x 400 LVL
Floor beams	(2x) 600 x 126 LVL
Shear walls	(8x) 5000 x 300 Post-tensioned precast concrete

The above-ground structural system for the *Optimum 'Hybrid'* design has a timber (LVL) framework (columns and floor beams), timber (CLT) stress-skin upper floors, post-tensioned precast concrete shear walls and a steel roofing system – a true mixture of timber, concrete and steel materials.

The following is a summary of the selection of components / systems for the *Optimum 'Hybrid'* design building.

PURLINS

(The roof is pitched and clad with long-run metal roofing or metal sandwich panel roofing).

Both timber and steel purlins are suitable in terms of overall performance provided that they are afforded the correct protection / treatment.

Steel has a significant advantage over all the alternatives in terms of cost.

RAFTERS

(The roof is pitched and clad with long-run metal roofing or metal sandwich panel roofing).

All the materials considered for the roof structure have similar performance characteristics provide they are afforded the correct protection or treatment. Bolted LVL, glulam and steel have all been used successfully. LVL would be slightly more expensive, whilst steel is both lighter and smaller. The bolted connection of steel purlins to steel rafters has some advantages.

For these reasons, steel has been selected as the optimum material for the rafters along with steel bracing.

UPPER FLOORS

(The upper floors are rigid diaphragms which are critical components of the buildings structural system. The suspended floors facilitate the transfer of seismic energy, in the horizontal plane, to the vertical shear walls).

All the materials considered for the upper floors are suitable in terms of general performance. A timber stress-skin floor has more advantages than disadvantages when compared with the other systems. It is relatively light-weight, fast to install and it has no need for an in-situ concrete topping and temporary propping, all of which suggest a significantly shorter construction period and a viable alternative to the more traditional concrete floor systems. Of the stress-skin options, the CLT composite appears to be slightly more economical and, due to its large panel size, faster to install, with no concrete topping to be poured.

For these reasons, the CLT Stress-skin system has been selected as the optimum system for the upper floors.

THE STRUCTURAL FRAME

(The frame is a beam and column system primarily intended to carry vertical (gravity) dead loads and live loads within the building. A variety of bolted frames were considered in concert with a complementary system of shear walls).

All the systems and materials considered for the frame are suitable in terms of structural integrity provided they are afforded the correct protection or treatment. Frames comprising LVL, glulam, steel and concrete have all been used successfully in a variety of applications. LVL and steel are comparable in terms of most of the evaluation criteria, with glulam and concrete scoring less favourably.

Even though the initial material cost for steel is less than the alternatives, steel has limited natural resistance to fire and would require added protection in the form of fire rated coating or cladding, which would add significant cost. Connecting the timber floor to steel beams would require the addition of ribbon plates which would also add to cost and construction time. Such plates would not be required with timber beams.

Table 1. Results of structural element comparison for proposed building at 190 Hereford Street.

Component	System	Cost	Weight	Seismic performance	Component bulk/size	Acoustic performance	Fire resistance	Sustainability	Construction speed	Structure durability	Neighbourhood disruption	Score
		2 = economical 1 = acceptable 0 = uneconomical	2 = light 1 = heavy 0 = very heavy	2 = good 1 = acceptable 0 = poor	2 = small 1 = large 0 = very large	2 = good 1 = acceptable 0 = poor	2 = good 1 = acceptable 0 = poor	2 = good 1 = acceptable 0 = poor	2 = fast 1 = acceptable 0 = slow	2 = good 1 = acceptable 0 = poor	2 = least 1 = acceptable 0 = unacceptable	
Purlins	LVL	1	1	1	1	1	1	1	2	1	1	11
	Glulam	0	1	1	1	1	1	1	2	1	1	10
	Steel	2	2	2	1	1	1	1	2	1	2	15
	I-Joist	1	2	2	1	1	1	1	2	1	1	13
	CLT	0	0	0	1	1	1	1	1	1	1	7
Rafters	Bolted LVL	2	1	2	1	1	1	1	2	1	2	14
	Bolted glulam	1	1	2	1	1	1	1	2	1	2	13
	Bolted steel	2	2	2	1	1	1	1	2	1	2	15
Upper Floors	CLT (solid)	0	1	2	2	1	1	1	2	1	2	13
	Stress-skin	1	2	2	2	1	1	1	2	1	2	15
	Flat slab	2	0	1	1	2	2	1	1	2	1	13
	Interspan	2	1	1	1	2	2	1	1	2	1	14
	Metal Deck	2	0	1	1	2	1	1	1	2	1	12
Columns	Bolted LVL	1	2	2	1	1	2	1	2	1	2	15
	Bolted steel	2	2	2	1	1	0	1	2	2	2	15
	PC Concrete	1	0	1	1	1	2	1	2	2	2	13
Floor Beams	Bolted LVL	2	2	2	1	1	2	1	2	1	2	16
	Bolted glulam	0	1	2	1	1	2	1	2	1	2	13
	Bolted steel	2	2	2	2	1	0	1	2	2	2	16
	PC Concrete	0	0	1	1	2	2	1	1	2	1	11
Shear walls	PT CLT	0	2	0	0	1	2	1	1	1	1	9
	PT LVL	1	2	1	0	1	2	1	1	1	1	11
	PRESSS Conc	2	1	2	2	2	2	1	2	2	2	18
	Insitu conc	2	0	1	0	2	2	1	0	2	0	10
	Masonery	0	0	0	0	2	2	1	0	2	0	7
	K-Brace	0	2	2	2	0	0	1	2	2	2	13
Foundation	Screw piles	1	1	2	1	1	1	1	1	2	1	12
	Bored piles	1	1	2	1	1	1	1	1	2	1	12
	CFA piles	1	1	2	1	1	1	1	1	2	1	12
	Raft slab	1	1	2	1	1	1	1	1	2	1	12

Notes: No weighting has been added to the scores to account for some criteria being more important or relevant than others (weighting could affect relative score). All materials given the same score (1) where a particular criterion is not an important consideration. Disregarding any of the listed criteria may affect the total relative score.

For these reasons, bolted LVL has been selected as the optimum structural frame system.

SHEAR WALLS

(The shear walls are the main part of the bracing system intended to transfer seismic loads within the building to ground. The length of each shear wall has been standardised at 5 metres).

CLT shear walls were discounted, as they would require special composite construction. Concrete masonry walls were discounted as the plan dimensions required would be impossible to achieve with standard concrete blocks. Otherwise, all the materials considered are suitable in terms of structural integrity and earthquake-resistant design, provided they are afforded the appropriate protection or treatment. However, not all are equally suitable in terms of spatial requirements.

Precast concrete has advantages over - or is at least equal to - the alternative options in respect of all of the selection criteria, except weight. However, the lighter options have significant disadvantages in other areas.

It is considered desirable to use only one material for shear walls in the same orientation in order to maintain consistency in the structural behaviour of the walls during a seismic event. Therefore, the material chosen must be suitable in all applications.

For these reasons, post-tensioned PRESSS (pre-cast seismic structural system) concrete has been selected as the optimum material for all shear walls.

FOUNDATION SYSTEM

Given the potential complexity of the ground conditions around Hereford Street in Christchurch, the primary consideration for the selection of the foundation system is seismic performance. In terms of structural suitability, each foundation system has certain advantages over the alternatives depending on the specific circumstances and specific location.

At the time of this study, specific geotechnical information was not available so it was not possible to confirm what the optimum foundation would be. However, it is anticipated that the optimum foundation will incorporate a combination of systems.

ALL TIMBER 'DAMAGE- RESISTANT' STRUCTURAL SYSTEM DESIGN

The *All Timber 'Damage-resistant'* structural system design provides a comparison with the *Optimum 'Hybrid'* design. It is comprised of the optimum timber-based components identified in the optimisation study. The notable differences between the *All Timber damage-resistant* design and the *Optimum 'Hybrid'* design lie in the roof structure and the shear walls (see Table 3).

Table 3. Structural components in the *All Timber 'Damage-resistant'* structural design.

Structural component	Selected material / system
Purlins	360 x 90 HyJoist
Rafters	(2x) 400 x 126 LVL
Upper floors	CLT 320mm Stress-skin system
Columns	400 x 400 LVL
Floor beams	(2x) 600 x 126 LVL
Shear walls	(12x) 5000 x 400 post-tensioned LVL

'DUCTILITY 3' STRUCTURAL SYSTEM

The *'Ductility 3'* structural system was derived from the optimisation study and provides a comparison for a building with the minimum level of seismic resistance required to comply with the current New Zealand Building Code. This option has been included to quantify and illustrate the main differences between a 'damage-resistant' structural system and a conventional seismic resistant system.

The main difference between the *Optimum 'Hybrid'* design and the *Ductility 3* design is in the shear wall construction - (8x) 5000 x 300 reinforced in-situ concrete walls - with the former having post-tensioned concrete and the latter having standard reinforced in-situ concrete.

COST COMPARISON

Concept drawings and preliminary structural design issue documentation were prepared by ISJ and used by RBL to produce preliminary elemental construction cost estimates for all the building designs. Cost estimates are for the structural frame components only** (see Table 4).

For the three structural designs investigated, the *Optimum 'Hybrid'* design would be the more economical *damage-resistant* option with a total structural cost of

Table 4. Cost comparison of structural frame components for *Optimum 'Hybrid'* design and alternative designs.

Structural system	Cost of components of structural frame
Optimum 'Hybrid' damage-resistant design	$1,817,000
'All Timber' damage-resistant design	$2,435,000
'Ductility 3' structural design	$1,557,000

**Cost estimates based on historical data of similar projects and priced at rates established during April 2012. The level of pricing assumes a competitively tendered contract. Estimates do not include GST, consents and legal fees, consultant fees, insurance, construction contingency or cost fluctuations.

$1,817,000. The structural cost of the *All Timber* design option would be 34% more expensive at $2,435,000 – the main areas of cost increase are in the shear walls and the roof structure. The study shows that incorporating a higher level of seismic design - *damage–resistance* – using the same materials and structural configuration (including the same number of shear walls) would be approximately 17% more expensive than the more conventional *'Ductility 3'* structural design at $1,557,000. However, for the building at 190 Hereford Street, this conventional system is not suitable as the brief specified the utilisation of the latest technology to minimise earthquake damage as being very important.

In terms of the overall building costs, the differences described above are less dramatic. RLB expect that the cost premium for an *Optimum 'Hybrid'* damage-resistant design over a conventional *'Ductility 3'* design would be around 8% ($200 per square metre) of the total building cost and the cost premium for an *All Timber* damage-resistant design over the *Optimum 'Hybrid'* damage-resistant design would be around a further 11% ($300 per square metre).

The cost estimates indicate that the structure of the *Optimum 'Hybrid'* design (excluding the roof and sub-structure) would represent around 28% of the total building cost. This can be further broken down as being 30% for the frame, 26% for the upper floors and 44% for the shear walls. This implies that the shear walls (the element representing the most significant difference between the *Optimum 'Hybrid'* and the *'All Timber'* designs) makes up approximately 12% of the total building cost. Putting this in context, the additional cost, in terms of the total building cost, of the LVL over PRESSS shear walls in a damage-resistant design for this building is around 6%.

CONCLUSIONS

Multi-storey commercial buildings, such as that proposed for Hereford St. in Christchurch, are usually constructed of a variety of different structural materials – termed a 'hybrid' building. This study shows that there is no single material that is appropriate in all circumstances and the choice of structural materials will depend on defined selection criteria, which may be highly subjective. A slight shift in criteria may produce a building constructed of different materials.

Using the *right material for the right application* - as determined by a range of selection criteria – will often lead to timber components and systems being selected for many structural elements of a multi-storey building, in a cost-effective design.

The study has shown that medium-rise multi-storey timber buildings can be built at a cost comparable with conventional construction. The *Optimum 'Hybrid'* design used a mixture of timber, steel and concrete for the main structural elements, with timber components being used for the main gravity-load structure including the floors, beams and columns.

Designing a damage-resistant building to go beyond the conventional *Ductility 3* code requirements incurs a cost premium – in the case of this study around an additional 8% of overall cost. An *All Timber*, structural design with timber components for all the main structural members would incur a further 11% cost. When viewed as a percentage of the total building cost, these premiums are relatively small and may well be within the affordability range of building owners and developers if they consider these to be important features.

The alternative costs for the three designs reflect the best estimates from a major firm of quantity surveyors for current forms of construction. It is anticipated that the cost of new timber materials and damage-resistant designs will become more competitive in due course, as they become more widespread in the construction industry.

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