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Crane erection of timber-trussed rafter roofs

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Traditional methods of timber frame construction are labour-intensive and time-consuming. This paper details a study of the crane-erect method of construction which utilises on-site preparatory work and off-site fabrication. The paper also examines the project planning alterations and implications which are required for crane-erect construction to be successful and the feasibility of crane erect with regard to improved time, cost and safety.

1. INTRODUCTION

With the foreseen expansion in the timber frame market—Smit[1] and Guthrie[2] reported an estimated increase to a 37% share of a 190 000 new-build market by 2008 compared to the 15% share of 162 000 in 2001—due to environmental and economical issues there will be increased pressure on contractors to deliver construction projects on time and within budget.

Traditional methods of timber frame construction, when compared with crane-erect, are labour-intensive, time-consuming and relatively high risk, the major risk being working at height. The Health and Safety Executive,[3] whose study examined the whole construction industry, recognised the associated risk of working at height by reporting that over the past five years there have been 437 fatalities on construction sites in the UK of which 225 were as a result of a fall from height. This equates to almost one person being killed every week on average.

Crane-erect construction allows for the preparatory construction at ground level of the roofing systems which are then lifted into place. This results in a large reduction in time spent working at height and also optimises the procedure of domestic dwelling construction. Clients appear to be sceptical about the benefits in time, economy and safety brought about by the crane-erect system, but this study will show that their findings are misplaced.

2. CRANE-ERECT CONSTRUCTION

The major components of a timber frame dwelling can be pre-assembled. Taking the construction of these components to a factory environment alleviates the problem of the current construction industry skills shortages, provides a safer working environment and is also proven to have a higher level of best practice production time.[4]

Pre-constructed wall panels and flooring systems (Fig. 1) require a revised method of on-site construction and best practice is to use a crane. This allows wall panels and floor cassettes to be lifted into position during the construction process and results in limited man handling and reduced erection time.

Since construction of the roofing system at height normally poses a major risk in the construction process[5] engineering this out by construction of the roof at ground level and then craning into position gives a far safer method which is being adopted by some of the more safety-conscious erectors.

(a)

(b)

Fig. 1. System components: (a) wall panels; (b) cassette floors

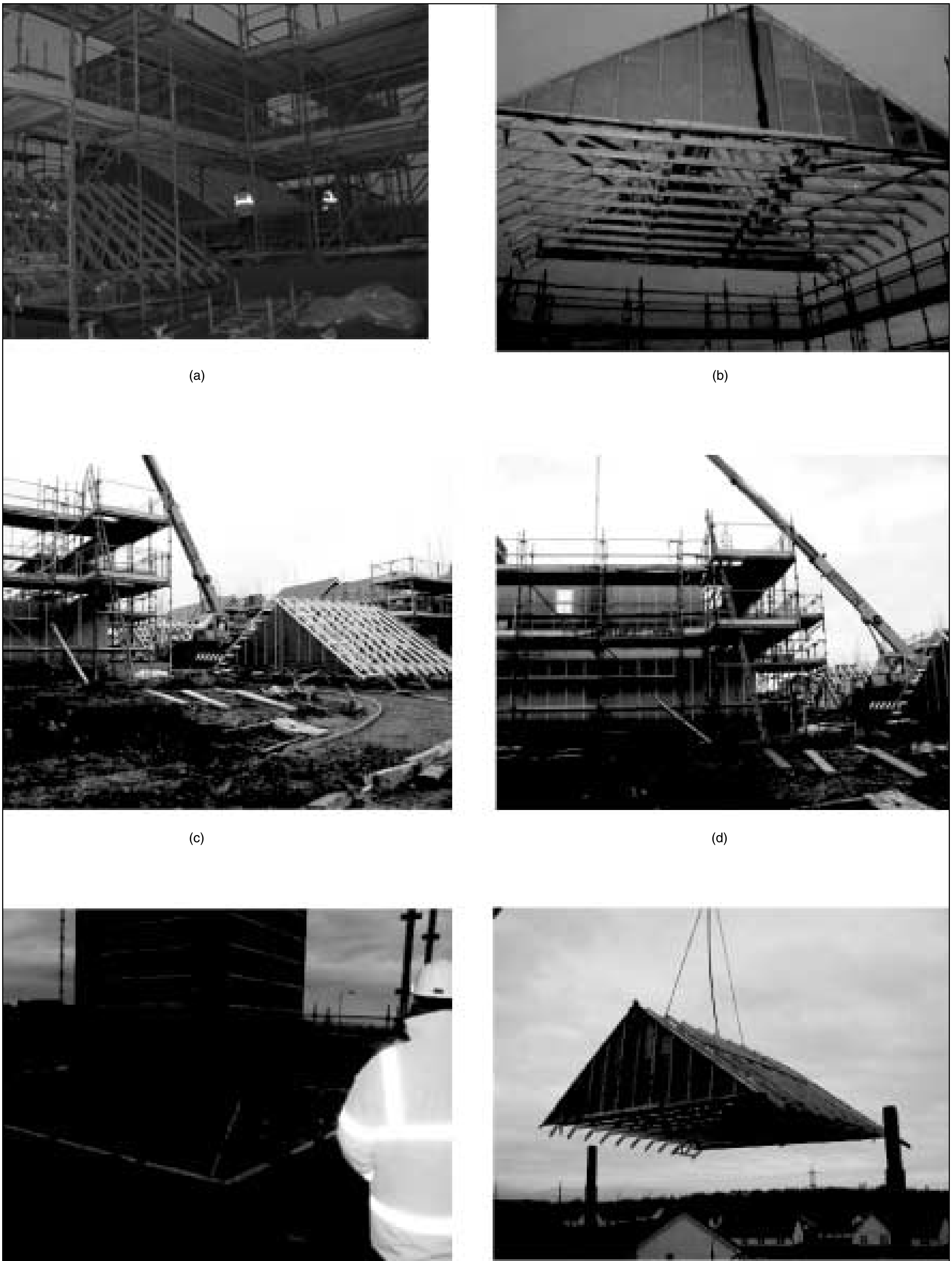

Fig. 2. Construction process: (a) roof constructed on ground-floor slab; (b) roof lifted out of position; (c) ground-floor panels erected; (d) and (e) cassette flooring and first floor panels installed; (f) roof system craned into position

An erection procedure was therefore developed to encompass construction of the floors, roof and walls using a crane. This construction method is known as crane-erect (Fig. 2) which the authors believe is the future best-practice procedure for the erection of timber-framed structures.

3. PREREQUISITES

For the crane-erect method of construction to be carried out safely and efficiently there are certain prerequisites.

Studies have shown that there is a change in the risk of accidents by committing to off-site fabrication and on-site preparatory work. The accident rate switches from minor consequence and high risk to major consequence and low risk.[4] It is imperative, therefore, that good construction, design and management procedures are implemented.[6]

At the design stage the risk of failure due to lifting of the component should be engineered out.

(*a*) Any system component being craned into position should be designed for this purpose and the weight of the component should be supplied to the on-site staff.
(*b*) Lifting points must be designed and, if required, manufactured into the products to be lifted.

This will have implications at design and manufacturing level, resulting in increased factory work load; however, the increased time spent carrying out these tasks is seen as minor in comparison to the on-site advantages gained.

The success of crane erect is reliant on good project planning. The delivery sequence of components should allow for the construction of the roof system at ground level prior to other construction events. Just-in-time principles are necessary to limit the need for storage, especially on constrained sites. The crane requires adequate space being made available in close proximity to the plot being developed and a designated area for the temporary storage of the pre-constructed roof system within its lifting range.

Project planning has to ensure that other trades will not be disturbed or indeed any risk to others created from the congestion of activities in a confined area. For this reason the crane-erect method lends itself to larger-scale projects and those on green- and brownfield sites. On small-scale and congested sites, the planning of activities is more difficult to allow for crane erect, although in most circumstances not impossible.

Good infrastructure for ease of access, unrestricted visibility, a predetermined temporary storage area for the constructed roof system and no overhead hazards are further prerequisites.

In normal circumstance the prerequisites are raised at the pre-start meeting of the construction project. To make this process simple in the future, partnering will be beneficial. If the client and the erector have a mutual understanding they can tailor their planning to work in tandem, resulting in operational efficiency.

The starting point for safe and efficient construction is training. The primary requirement is for safe working practice when carrying out lifting procedures and for this reason all those involved in the erection process must be approved slingers and signallers and those who deal with the planning of the erection process should be appointed persons, in line with the Health and Safety Executive guidelines.[7] There is also a requirement to produce a lifting plan and method statement for every building.

4. FEASIBILITY STUDY

To provide evidence of the benefits of the crane-erect method of construction a feasibility study was conducted. Three main areas were investigated: safety, time and cost.

The health and safety statistics available are not specifically related to crane erect, so to alleviate client scepticism a study was carried out of the different methods of erection and their associated risks. The study conducted used weighted risk assessments of the different methods of timber-frame construction to determine which one had the lowest associated risk. The risk assessments were completed by people at all levels of the erection process, including site managers, contract managers, erectors and health and safety officers. The outcome of the study showed that there was 65% less risk of an accident occurring using the crane-erect method of construction.

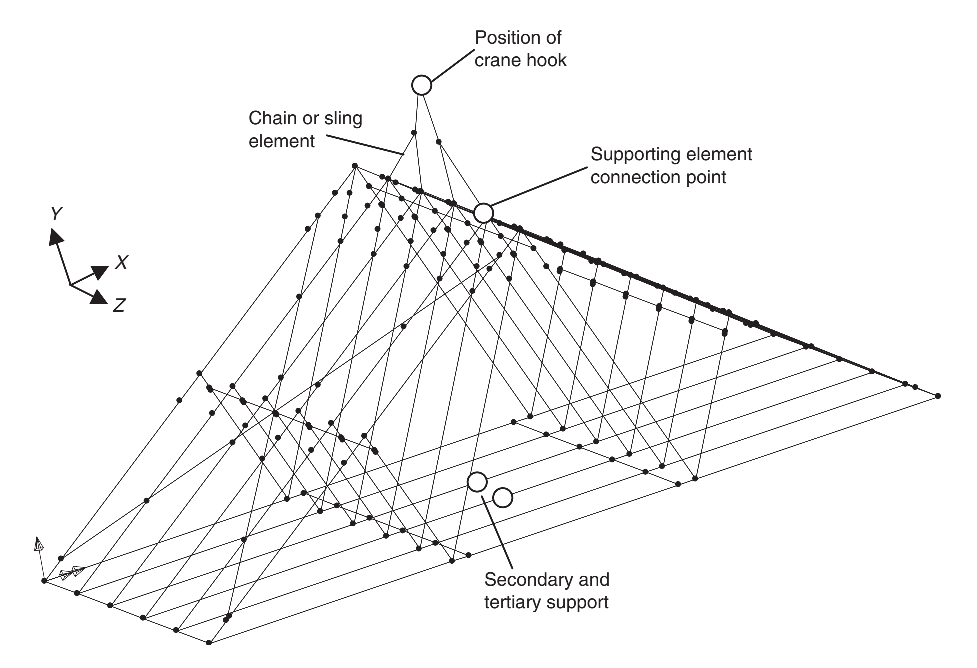

Fig. 3. Support conditions

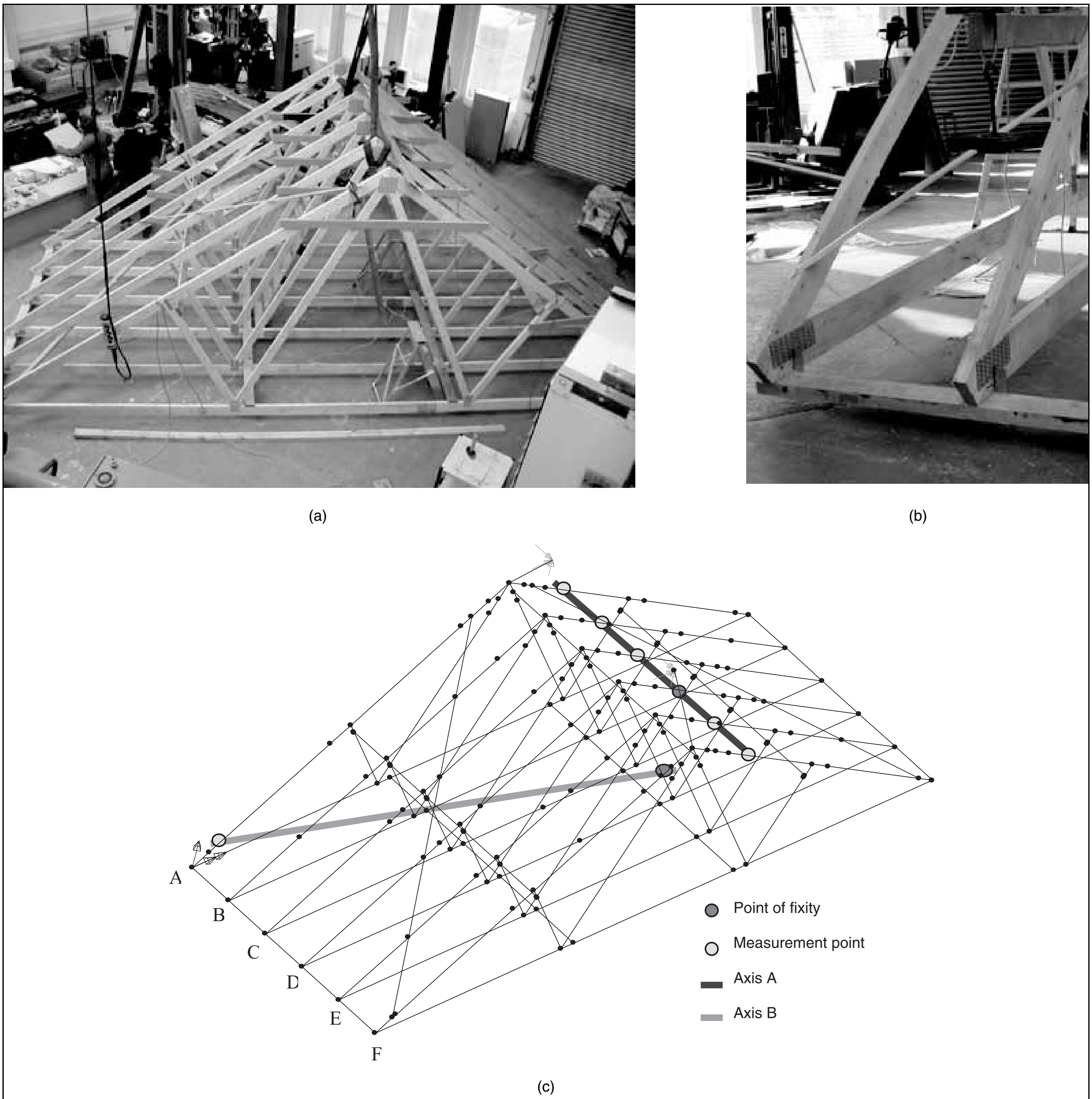

Fig. 4. Laboratory testing and analytical model: (a) laboratory set-up; (b) eccentric load; (c) analytical model

Time and cost are very much interlinked and there is a trade-off between the two variables. Construction planning involves the selection of proper methods, crew sizes, equipment, and technologies, to perform the tasks of a construction project. In general, there is a trade-off between the time and cost to complete a task: the less expensive the resources, the longer it takes to complete an activity.[8] Using a project planning tool, Microsoft Project, the different methods of timber-frame construction were compared to assess time-saving benefits. Each method of construction was broken into tasks and each task allocated resources and time requirements. From the study, crane erect was proven to produce a time saving of 53% if planning and resource allocation were optimal.

The time performance of crane erect is dependent on best-practice procedures being implemented. Allocation of resources, and in particular the time and cost of having a crane, is important. Good planning and training are required for operational success.

It is believed that additional cost incurred by the erection company, due to increased crane hire and training, will be counterbalanced by erection efficiency and improved safety. Client satisfaction in time will result in increased work load, leading to improved turnover and profitability.

Safety is of paramount importance when considering the implementation of the crane-erect procedure, as it eliminates the majority of the risks associated with timber-frame construction. Time and cost savings through adoption of crane-erect methods have been proven to be possible by good

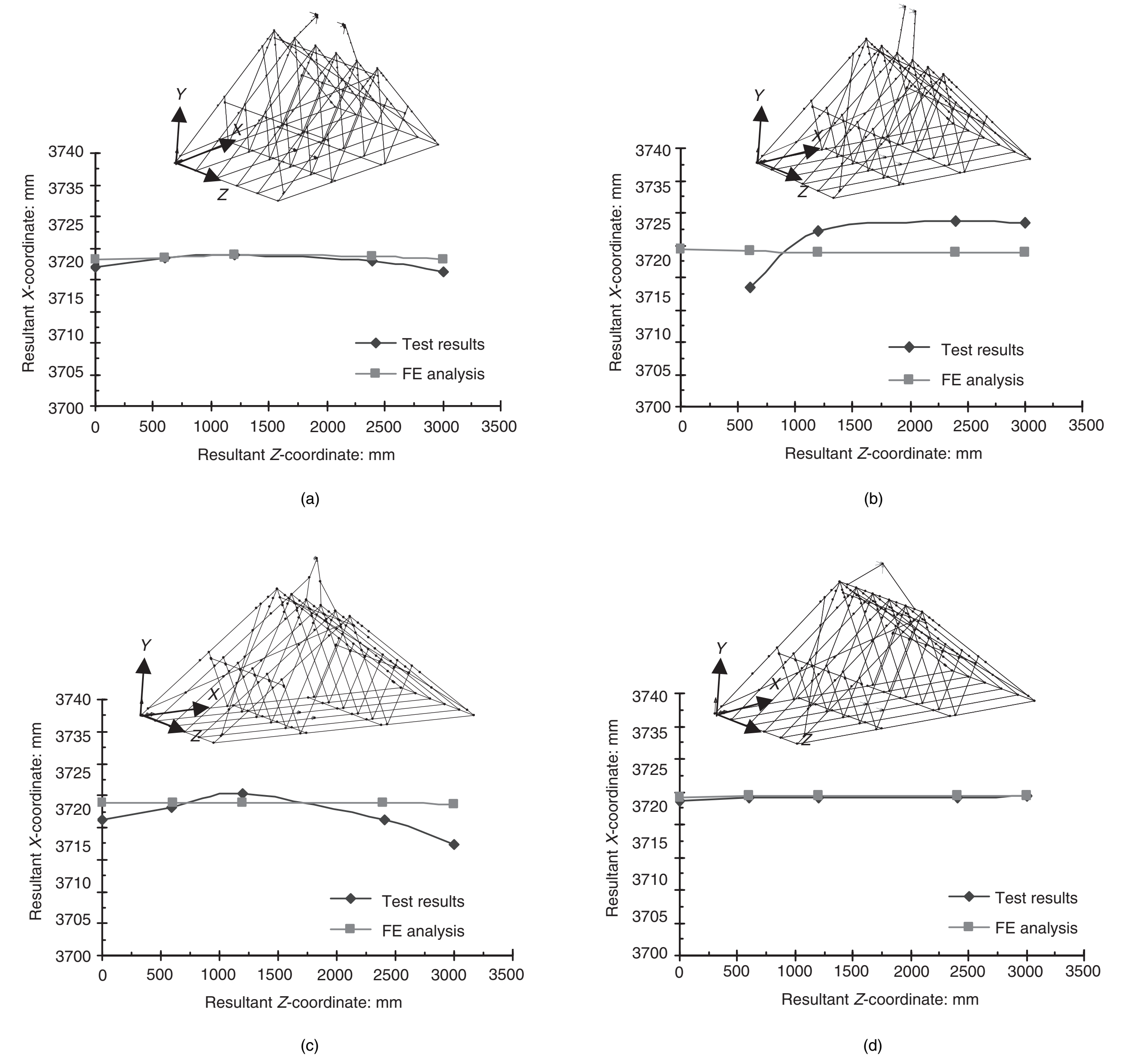

Fig. 5. Comparison of sample analysis and test results: (a) two-point lifting from apex; (b) two-point lifting from apex; (c) four-point lifting from apex; (d) two-point lifting using a spreader bar at apex

planning. This information can be used to alleviate client scepticism.

5. BEST-PRACTICE LIFTING PROCEDURE

The greatest risk associated with the crane-erect method is the lifting into position from ground level of the prefabricated roof system. For safe lifting procedures to be implemented, the structural integrity of the system must be assured.

5.1. Analytical modelling and laboratory testing

A three-dimensional truss system was modelled using the structural analysis software LUSAS. Wind loading was not considered in the analysis as lifting during adverse weather conditions would be hazardous and therefore never undertaken. After model verification different lifting conditions were analysed to investigate how the system reacted. This was used to develop a best-practice procedure. The analytical model was verified by testing of a roof system in the laboratory.

Analytical modelling of the system during lifting conditions was undertaken to give a response representative of the actual system under the equivalent conditions. The lifting conditions limit the support restraints of a system to one point: the 'crane hook'. Modelling of such support conditions is not feasible; the computer model would fail due to lack of restraint, and therefore, the model had to be given extra restraint for successful analysis. Two extra restraint points were placed at the mid-span of the bottom chord of the middle two trusses of the system (Fig. 3), restricting transitional movement of the system in the *X* and *Z* directions.

How well this model represents the actual system was unknown and for this reason laboratory testing of the modelled system was undertaken to provide results for verification. The testing of the system under lifting conditions is not without complications. The measurements taken from the system under imposed lifting conditions have to be practical to measure, have a good degree of accuracy and be suitable to allow comparison for analytical model verification.

The most practical measurements to be taken are those of deflection. On lifting, the system is suspended in space and susceptible to sway, therefore deflection measurements of the system components must be made relative to a fixed point on the system itself. The deflection measurements made then have to be processed for comparison with the analytical model output.

Two measurement axes on the system were set up, namely axis A and axis B (Fig. 4), to measure the deflection of the system and nine laboratory tests were conducted. For each lifting test the resultant local deflection of the node points was measured relative to the fixed point and then converted to global deflections and compared to the computer analysis. Sample plots of top chord deflection show the correlation between the analytical model and the laboratory test results (Fig. 5).

The method of testing would have a bearing on the sensitivity of the results. Lifting using a spreader bar diminishes the margin for error due to even strain being placed on the system whereas the results from point lifting are dependent on the configuration of the lifting equipment. Applying lifting points to the analytical model does not account for uneven configuration of lifting equipment, which results in the overstraining of lift points, therefore some discrepancies between the results were expected.

To further prove that the laboratory test results correlated with the analytical model output a rating system was set up to compare the conclusive statements taken from each test with the expected accuracy of results due to the nature of the testing procedure (Table 1). The purpose of the table is to average out the results to show whether the testing process provides evidence to support the analytical model as being a good representation of the truss system being lifted.

The end result of the weighted comparison is a value of 5·25, giving further evidence that the laboratory testing provided results of 'excellent' conclusion rating but of 'depleted' accuracy (Table 2) due to the nature of testing and this was true of the testing scenario.

From the laboratory testing the following was also concluded.

(*a*) It is possible to model roof systems under lifting conditions reasonably accurately.

Test	Overall conclusion*		Accuracy factor†		Total
1a Two-point apex	Good	2	Good	0·75	1·50
1b Two-point apex	Good	2	Good	0·75	1·50
2a Two-point apex	Sceptical	−1	Good	0·75	−0·75
2b Two-point apex	Sceptical	−1	Good	0·75	−0·75
3 Four-point apex	Favourable	1	Average	0·50	0·50
4 Four-point rafter mid-point	Sceptical	−1	Depleted	0·25	−0·25
5 Spreader bar at apex	Excellent	3	V. good	1·00	3·00
6 Four-point rafter mid-point with eccentric load	Favourable	1	Depleted	0·25	0·25
7 Spreader bar at apex with eccentric load	Favourable	1	Depleted	0·25	0·25
				Total	5·25

*Overall conclusion ratings are taken from the conclusive statements of each test comparison.
†Accuracy factor is a prediction of how accurate the testing results will be depending on the nature of testing.

Overall conclusions ratings	Accuracy factor
Error = −3	Depleted = 0·25
Poor = −2	Average = 0·50
Sceptical = −1	Good = 0·75
Favourable = 1	V. good = 1·00
Good = 2	
Excellent = 3	

Table 1. Weighted comparison

Conclusion rating	Accuracy factor	Number of tests	Output
Error	Very good	9	−27·00
Error	Depleted	9	−6·75
Excellent	Depleted	9	6·75
Excellent	Very good	9	27·00

Table 2. Result scenarios

(*b*) The analytical model was stiffer than the actual system. However, this is conservative as it limits the load-sharing capacity of the system.

(*c*) Laboratory testing has shown that equal load distribution at lifting points is highly unlikely but with good procedures even lifting of the system can be achieved.

(*d*) Using a spreader element is the most effective means for applying an even distribution of load.

Considering the above points, the model was used to develop a best-practice method of lifting which optimised the load sharing of the system and also functioned in a manner which engineered out the risk of system failure.

5.2. Optimum lifting procedure

The calibrated and verified computer model was used to analyse a series of different lifting conditions to determine an optimum lifting method. Wind loading was not considered because lifting operations are deemed to be too hazardous during adverse weather conditions. Safety and practicality were the main optimising criteria. The major safety consideration is structural integrity during lifting because any failure could result in an accident of major consequence. For structural integrity the main criteria set for initial lifting method comparison were: even distribution of stresses between system elements, even support reactions and minimum system deflection. Examples of analysis of

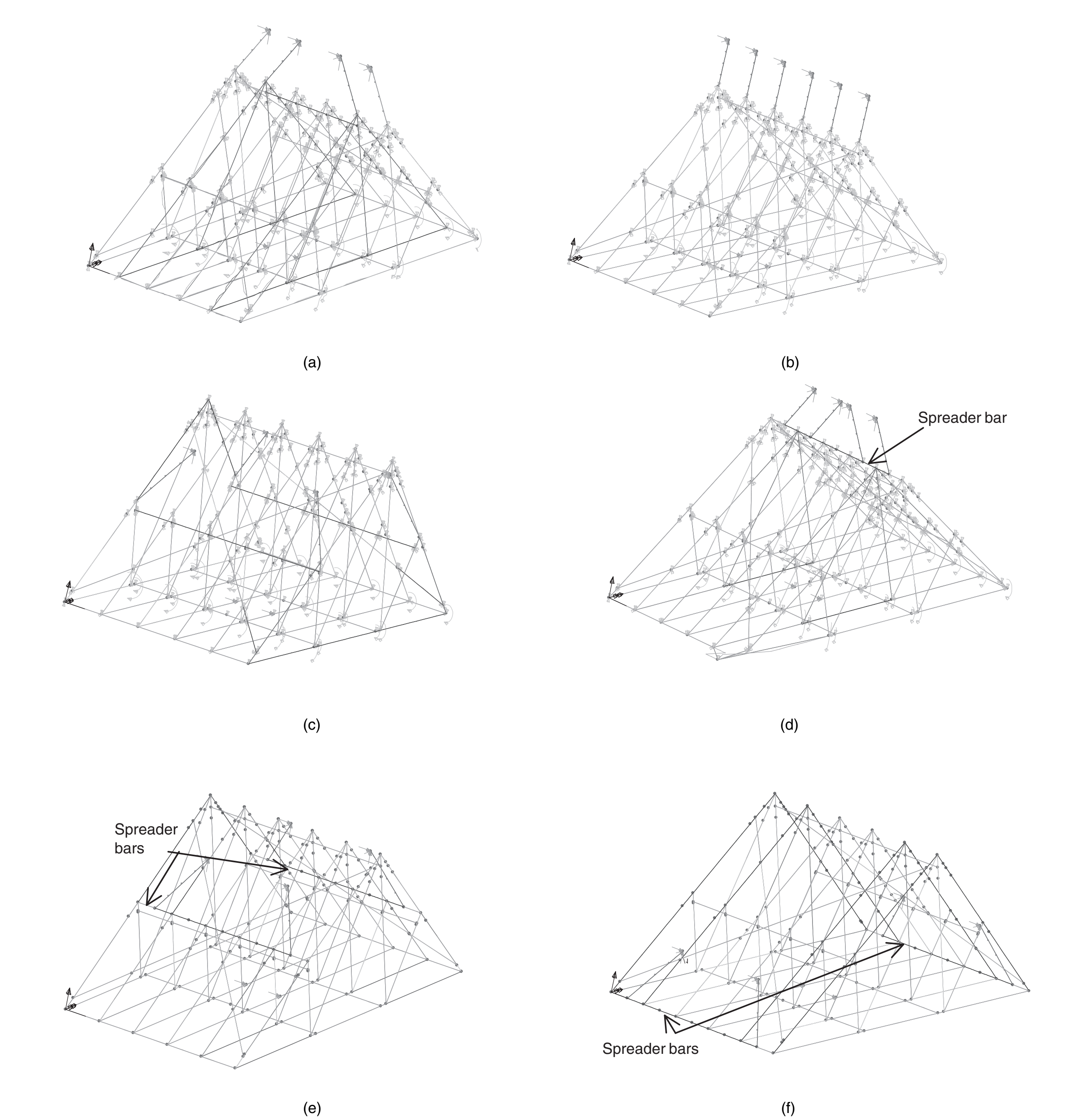

Fig. 6. Sample lifting analysis: (a) four-point angled apex lift; (b) optimum apex lift; (c) four-point angled rafter mid-span lift; (d) four-point spreader bar at apex lift; (e) four-point spreader bar at rafter mid-span lift; (f) four-point spreader bar at headbinder lift


Fig. 7. T-section roof system

the truss systems under different lifting conditions are shown in Fig. 6.

From the lifting analysis, it was concluded that apex point lifting from a spreader bar was the optimum solution in terms of safety and practicality. Lifting directly from node points on the system with the lifting equipment set such that lifting forces act in the vertical plane eliminates out-of-plane deflection of the trusses. Additional stiffening and strengthening of the system is not required. The number of lifting points required can be optimised for practicality, and apex point lifting allows the lifting of T-sections (Fig. 7) and other roof shapes because the configuration of lifting equipment is a simple procedure.

Lifting from every apex point is not practical so the next stage of development was to reduce the number of apex lifting points without compromising safety. The developed method was to require no extra system bracing and also be generic to all roof systems.

To develop the best-practice lifting procedure a model representative of the largest run of trusses to be lifted was created. This model was then used to calculate the optimum number and positioning of lifting points.

The specification of diagonal and chevron bracing is dependent on individual circumstance and therefore can not be relied upon in all cases for stability; for this reason only longitudinal bracing was modelled.

The roof system section modelled may form part of a larger system consisting of extra sections such as hipped ends or T-sections. Differential movement of the system section is avoided by providing adequate support to the whole of the system.

The initial analysis to optimise the number of lifting points assumed that the occurrence of system failure would be from shear or bending forces in the bracing or headbinder elements of the system. Final design checks were then made on the optimised lifting procedure to ensure that the load-carrying capacity of the system connections was not breached. Fig. 8 shows examples of the best-practice procedure developed from optimising the lifting points.

5.3. Site recommendations

For the best-practice procedure to be applied safely on site the following recommendations are made.

(*a*) Method statements and risk assessments will be produced and provided to on-site staff prior to execution of the work.
(*b*) It is a health and safety requirement that the weight of anything which is to be lifted is known and supplied to site. For this reason Table 3 was produced and used to calculate an estimated mass for every truss roof system to be lifted. The information provided in this table is relevant only to a specific range of truss roofs and uses the pitched roof area, not the plan area, of the roof.
(*c*) From the estimated weight of the roof the size and positioning of the crane is determined.
(*d*) Any operations to be carried out must be in line with site regulations.
(*e*) Lifting operations are not to be carried out during adverse weather conditions as attempting to control the system during the lifting procedure would be hazardous.
(*f*) Quality assurance procedures on site should ensure that all system elements are in good condition prior to construction through visual inspection.
(*g*) Gable panels are tied into the system by attachment of the bracing elements, and the diagonal bracing elements

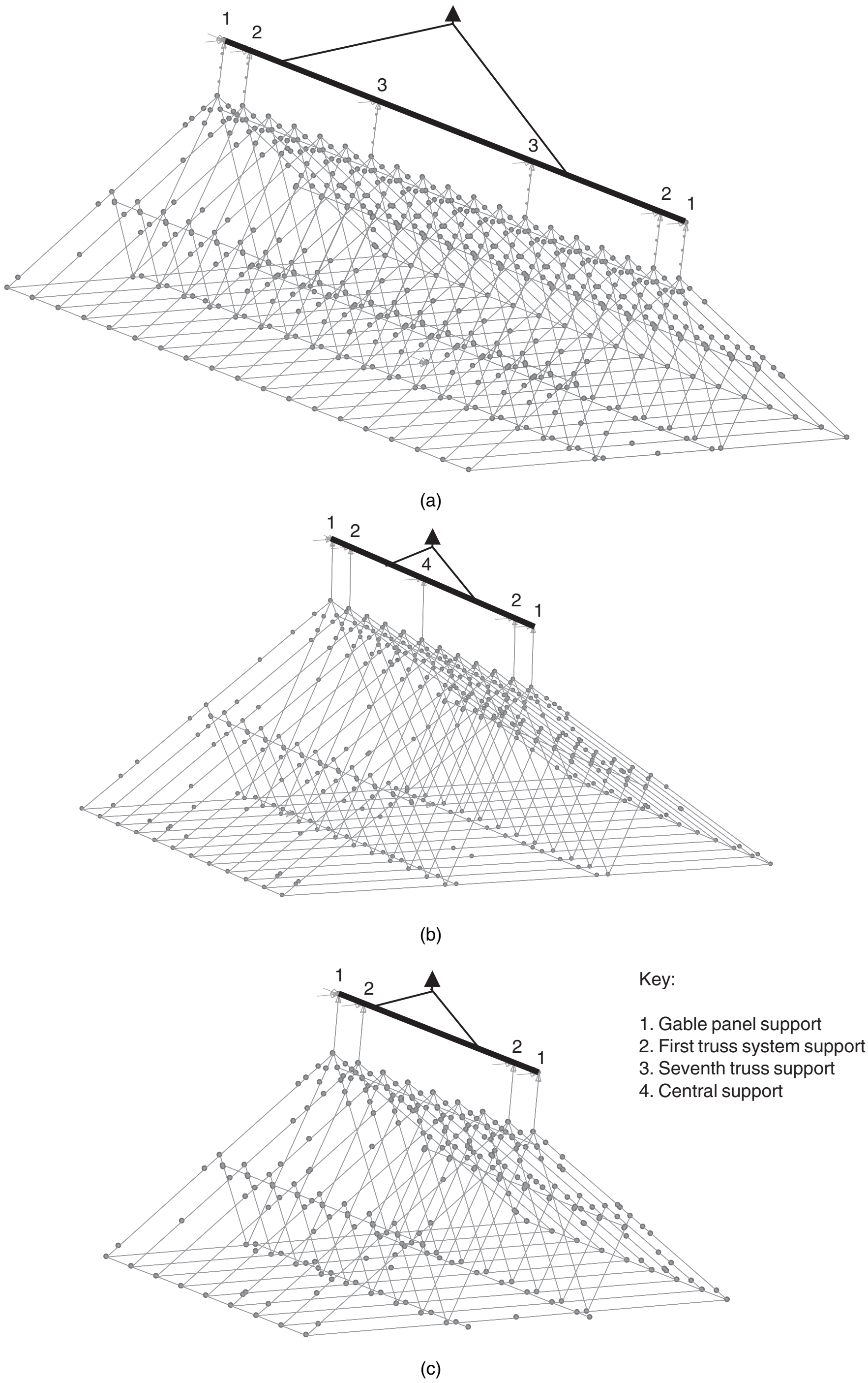

Fig. 8. Optimal lifting points: (a) large system with more than ten trusses; (b) medium-size system with seven to ten trusses; (c) small system with less than seven trusses

will also be fixed to the headbinder of the system (Fig. 9).

(*h*) All fixings are secured in accordance with the fixing specification.

(*i*) The truss system is lifted and fixed into position as follows.

- (i) Lifting will be carried out using a specified spreader bar and chains/slings as provided which have been designed, checked and verified for safe working loads.
- (ii) The chains/slings should be fixed to the pre-specified apex points which have been designated in accordance with the optimal lifting points (Fig. 8).
- (iii) Strain is placed on the chains/slings evenly such that the lift is level and optimum load spread is achieved.
- (iv) Gable panels are supported from the onset of lifting to eradicate the risk of failure in the headbinder.
- (v) Chains/slings are applied with care to restrict movement during the lift and also limit the risk of damage to bracing elements. On lifting, the chains/slings are to be vertical to restrict out-of-plane distortion of the trusses.

6. SUMMARY

The crane-erect method of erecting timber frames uses off-site

Pitched roof area: m^2	Truss system only: kg	Mass Unsarked: kg	Mass sarked: kg
30	301	411	602
40	401	548	803
50	502	684	1004
60	602	821	1205
70	702	958	1406
80	803	1095	1607
90	903	1232	1807
100	1003	1369	2008
110	1104	1506	2209
120	1204	1643	2410
130	1304	1780	2611
140	1405	1916	2812
150	1505	2053	3012
160	1606	2190	3213

Table 3. Truss mass calculator

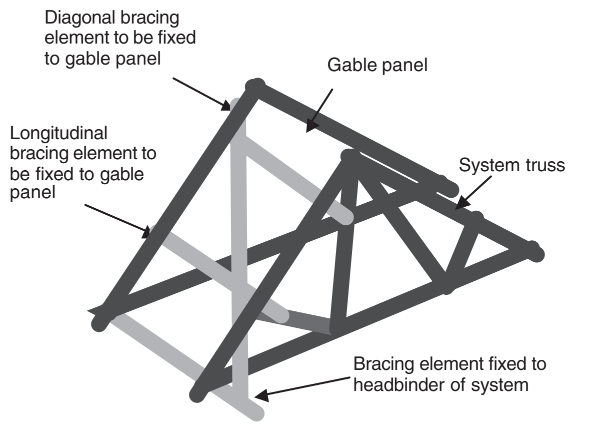

Fig. 9. Bracing details

fabrication and on-site preparatory work to optimise the construction process. With the implementation of good project planning and improved on-site practices, the crane-erect construction method is a quicker, more cost-efficient and safer practice.

The development of a best-practice lifting procedure has engineered out the major hazard of working at height and reduced the risk of system failure during lifting to a negligible amount.

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