A support system for a good practice approach to the conceptual design of tubular space bridges

W. Tizani[1], A.S. Whitehead[1], A.R. Greig[2] and S. Blackman[3]

ABSTRACT | The construction of large bridge projects is a complex and fragmented process. The design and construction of bridge decks made with tubular space structures is no different. These structures offer a structurally efficient solution but they are considered expensive because of the cost of fabrication associated with complex geometry at the connections and the amount of manual welding required.

This paper describes the result of a study aimed at making such a solution more viable. This is done through the development of a semi-automated welding system, to reduce fabrication costs, and the implementation of an IT enabled 'good-practice' design process, to effect an integrated and construction-led approach to the design.
The study has led to the integration of the different facets of the design process while also taking into account practical considerations involved in the fabrication. This has been achieved by the implementation of the above in experimental software to assist the designer during the conceptual design stage.

KEYWORDS | business-process, good-practice, integration, design, tubular steelwork, fabrication process, welding

1 Introduction

The construction of large bridges is a complex and fragmented process. The work necessary for the structural design, fabrication and erection is divided between a number of organisations. This causes problems with the flow of information, the division of responsibilities and may lead to the possibility of having to do rework. This is especially true when the preliminary design process concentrates on producing structurally efficient and safe structures without sufficient attention to practical issues dealing with fabrication and erection.

Tubular space frames are efficient structures, which have been proposed as alternative designs for new bridges. This type of structure distributes the load better than a series of beams. Typically 50% of the structure of a plate girder bridge is dedicated to supporting itself rather than the load. This may be reduced to less than 30% with a space-frame design [1].

However, construction of a large space frame bridge incurs increased fabrication costs due to the greater complexity of welding at the nodes where the intersecting tubular members meet, Figure 1. The complex three-dimensional weld paths are much

1. School of Civil Engineering, The University of Nottingham, Nottingham, NG7 2RD, UK
2. Department of Mechanical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK
3. Welding Engineering Research Centre, Cranfield University, Cranfield, Bedford, MK43 0AL, UK

Figure 1. Typical node at bottom chord (Cleveland Bridge UK Ltd)

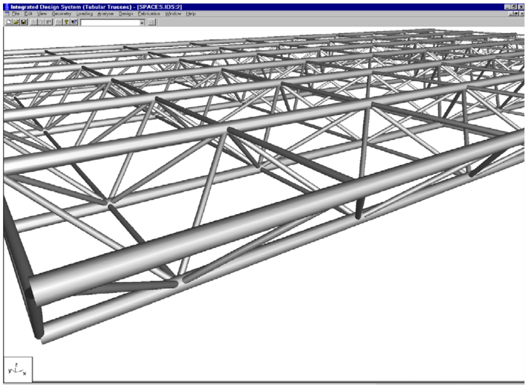

Figure 2. A general view of the SPACES frame

more costly to produce than the relatively simple two-dimensional weld paths found in conventional bridge designs. In addition automatic or robotic welding technology can be used for two-dimensional welds but is not currently available for the welding of tubular connections. A significant proportion of the cost of building a space frame bridge therefore resides in the fabrication and assembly of members, and this can easily outweigh the saving in steel weight.

For any given span and bridge loading, the space frame involves a repetitive lattice structure, Figure 2, and the brace-chord nodes can be grouped into a small number of similar designs that are repeated throughout the structure. Hence, as there are a large number of complex welds of similar design, it was considered that an automated welding system might be more cost-effective than manual welding and provide both increased productivity and improved quality.

Improvements are also possible if the whole production system is considered more carefully at the conceptual design stage and a more integrated approach is followed. A study was undertaken with a view to improve the entire process from conceptual design to site-erection. The study aimed to devise an automated welding process and equipment to improve the productivity of such a welding-intensive structure, to improve understanding of the design, manufacture, inspection and installation of 3D steel structures, and to develop a decision support system for their design. The study has used the SPACES bridge system, developed by Maunsell-MSP, as a proof of concept. It involved:

- the conduct of a field-trial fabrication of a sub-assembly of a SPACES bridge to study the practical issues involved with implication for the design stage and for the feasibility of using automatic-welding techniques
- the development of a prototype welding system for tubular nodes that is capable of addressing the practical issues arisen from the field-trial
- the mapping of a good-practice approach to the design and fabrication for such structures
- the implementation of the good-practice approach in a computer-based decision support system

This paper reports on the outcome of this study and concentrates on the description and the implementation within software of a good-practice approach to the design of such structures.

2 A field trial of the fabrication process

The aim of the trial was to identify processes that can be improved by decisions made at the design stage and to evaluate the parameters that an automatic-

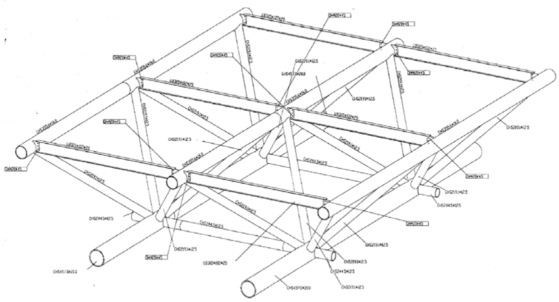

Figure 3. Drawing of the assembly used in frabrication field-trial

Figure 4. Part of the manufactured sub-assembly (Cleveland Bridge UK Ltd)

welding apparatus should have in order to be operated effectively on such complex weld geometry. A full-size sub-assembly of a bridge deck has been fabricated by a specialist steel bridge contractor and is illustrated in Figure 3. The sub-assembly was 9680mm wide 12106mm long and 2906mm deep. Figure 4 shows part of the fabricated structure. All tubular members were dimensionally inspected, cut and prepared using a numerically controlled machine and the joints were manually welded. The assembly activities were recorded, and data on tolerances fit-up and weld distortion and shrinkage were gathered. Dimensional analysis of the assembled prototype structure was used to model the assembly process and assess the fabrication and construction tolerances that could be achieved on a complete bridge structure.

2.1 Determination of parameters to enable automatic-welding

Welding is required to connect the brace members to the chord members. The welding procedure will depend on the welding specification and the gap that exists between these two members after being prepared for welding. A small gap is required to achieve weld penetration but a large gap will be more difficult to bridge and might require multi-pass solution or 'buttering'. Most critical would be the so-called root gap (gap at the toe of the brace, Figure 5). The expected variation in the root gap is considered the most important factor influencing the use of a fully automated welding system. A computer programme based on a mathematical model of the geometrical relationships and the assumed tolerances was used to ascertain the maximum and minimum root gap variations along the weld path. The model included length, ovality and wall thickness tolerances due to the manufacture of the tubular members as well as fabrication tolerances. Two sets of tolerances were used: documented tolerances provided by the steel supplier, Table 1, and measured tolerances taken from the field trial, Table 2. These variations were calculated by finding the 'worst case' combination using the various tolerances involved.

Table 1. Dimensional tolerances as provided by steel supplier

Dimension		Tolerance
Outside Diameter		± 0,5 mm or ± 1% which-ever is the greater
Thickness	Welded	± 10 %, with a minimum of ± 0,4 mm
	Seamless	+ 15 % - 12,5 %, with a minimum of ± 0,4 mm
Mass		± 06 %
Straightness		Maximum 0,2 % of the total lenght
Lenght		+ 6 mm, - 0 mm

Table 2. Measured tube tolerances

Section	Diameter (mm) Max	Min	Thickness (mm) Max	Min
219.1 x 12.5	220.24	218.21	12.83	11.85
244.5 x 12.5	245.26	243.76	12.66	12.44
355.6 x 16	356.75	354.88	15.82	15.43
457.2 x 16	459.09	455.76	15.76	14.77

The estimated variation in the root gap based on the tolerances provided by the steel supplier (set 1) were in the order of ±13.4 mm for a brace to chord angle of 60 degrees and chord spacing of 4m. Such a variation is too large to allow for the possibility of automatic welding. However, relatively high values were expected since the documented tolerances tend to be conservative.

On the other hand, the root gap variations resulting from using the measured tolerances (set 2) were more comparable with the actual gaps measured during the field trial. These variations are given in Tables 3, 4, and 5 for various section diameters, chord spacing and brace lengths all of which are within the ranges expected for the SPACES bridges. The largest variation of the root gap is therefore expected to approximately be ±2.5mm with a probability of 81%. The model assumed that one end of the brace could be aligned perfectly and then analysed the effect of tolerances at the other end. The most important factor influencing root gaps was found to be straightness of the tubular members. This, therefore, needs to be given particular attention during the fabrication stage. The tolerance in the section diameters, on the other hand, appears to have relatively little influence. Whilst the root gap variation, of approximately ±2.5mm was acceptable for manual welding, it still presented problems for automated welding as welding trials found that a root gap of 1.5mm - 4.5mm was necessary to achieve a full-penetration root pass (i.e. 3mm ± 1.5mm), [3]. Therefore automated buttering (multi-pass) procedures would be required to allow for the welding of the anticipated range of root gaps.

Table 3. Variation in root gap for different section diameters+

Chord Diameter	Brace Diameter	Max Variation at the root gap	Prob
(mm)	(mm)	(mm)	(%)
406,4	219,1	± 2,36	81
457	219,1	± 2,4	81
457	224,5	± 2,37	81
457	273	± 2,31	81
508	219,1	± 2,42	81
508	244,5	± 2,4	81
508	273	± 2,36	81
559	244,5	± 2,42	81
559	273	± 2,4	81
610	244,5	± 2,42	81
610	273	± 2,41	81

+ Chord spacing = 4000 mm; Brace lenght = 3200 mm; Brace to chord angle = 51,3 deg.

Table 4. Varation in root gap due to variation in chord spacing+

Chord spacing	Brace Length	Brace to Chord Angle	Max Variaton at the root gap	Prob.
(mm)	(mm)	(Deg.)	(mm)	(%)
4400	4400	56.9	± 2.38	81
4600	4400	53.8	± 2.23	81
4800	4400	50.5	± 1.87	81

+ Chord diameter = 559 mm; Brace diameter = 244.5 mm; Brace length = 4400 mm

Table 5. Varation in root gap due to variation in brace length

Chord length	Brace to Chord Angle	Max Variaton at the root gap	Prob.
(mm)	(Deg.)	(mm)	(%)
3800	50.8	± 1.92	81
4000	53.1	± 1.81	81
4200	55.2	± 2.3	81
4400	56.9	± 2.38	81
4600	58.5	± 2.01	81

+ Chord diameter = 559 mm; Brace diameter = 244.5 mm; Chord spacing = 4400 mm

In conclusion, the maximum predicted root gaps were approximately 13.5mm (set 1) and 4.5mm (set 2). The first set was ignored since it depicts the worst theoretical case. The second is taken from a controlled fabrication environment and represents most cases but does not allow for field-conditions. Hence, an automatic welding system capable of single and multi-pass welding of gaps of 1.5 to 9mm (variation of ± 3.75) was adopted as it is considered to be practical for the vast majority of situations.

2.2 Recommendation for the fabrication process

A number of areas arose from the analysis of the field trial that needs special consideration during the design, fabrication and erection process:

Minimising the amount of welding: the amount of welding necessary for such a structure was validated as the main cost item during the fabrication process. This needs to be minimised by the design options, for example by maximising the distance between the nodes.

Distortion due to welding: up to six structural elements can be joined to a chord at a single node. This requires a large amount of welding in a very small area on one side of the chord. The amount of heat applied in this process can cause large distortions in the chord. Free ends were found to deflect by about 15mm, as illustrated in Figure 5. This distortion can cause a great many problems when the fabricated units are offered together during erection. Changes to the welding procedure would do little to avoid this distortion. Shortening the free end would reduce the end deflection, allowing an infill piece to be used as shown in Figure 6, but this would increase the amount of welding needed. Another solution would be to clamp the free ends to reduce the distortions, this may introduce residual stresses into the chord but would minimise the problems involved in the offering together of the units.

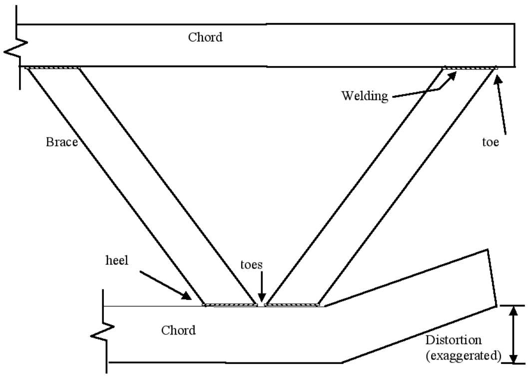

Figure 5. Welding distortion at free-end

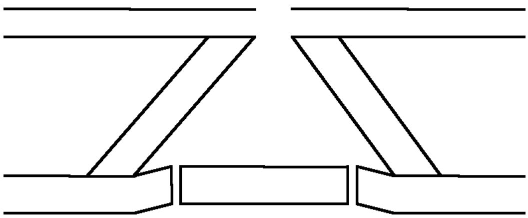

Figure 6. Use of in-fill section

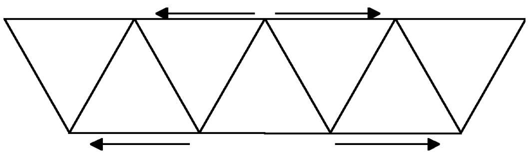

Figure 7. weld progress across the cross-section of the deck structure

Welding sequence: Welding should be carried out from the middle of the deck cross section outwards, first along the bottom nodes, with the top nodes following closely after, as shown in Figure 7. For safety reasons welding should not be carried out on the top nodes while the nodes below are being welded. This means any welding distortions will be symmetrical and will effectively reduce the width of the structure instead of warping it. Along the length of the assembly welding should progress down the length of the fabricated unit (Figure 8). Working along the structure means any longitudinal shrinkage will result in a shorter structure, as opposed to causing warping or buckling.

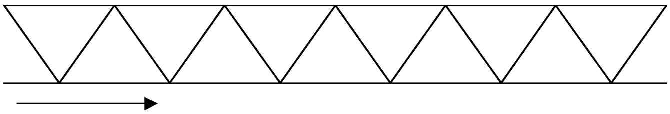

Figure 8. Work progress along the deck structure

Size of transported units: the sizes of SPACES assemblies quickly become too large to transport easily on the road. The inclusion of a temporary assembly yard either on or very near the construction site is key to stream lining the fabrication and erection processes. This could provide the sort of controlled environment available in the fabrication works, allowing the same quality of welding. This would also allow the cut and prepared members to be delivered to the assembly yard, either on or very near the site, where they would be welded into the erectable units and transported straight to the work face.

Sequence of fabrication: The fabrication process that was adopted during the trial had the following order: cutting, assembly, tack welding and finally full welding and surveying. The critical sub-processes were the assembly and tack welding. These adopted the following sequence: assembly of the bottom chords in the jig, completing any splice joints in the chords; assembly of the horizontal brace elements connected to the bottom chord; full inspection and level check of the bottom chord assembly; assembly of the top chords, again completing any splice joints; lifting of the top pipes into the jig; aligning the top chord assembly correctly relative to the bottom chord assembly; marking out the positions of the inclined braces on the top and bottom assemblies; assembly and tack welding the inclined braces; full dimensional survey to ensure the tubulars are level.

3 Design of welding system

Whilst articulated arm robots are now being used extensively to automate welding, their use is mainly limited to spot welds and single pass welds. To weld tubular structures is both geometrically and technically far more demanding but some previous work has been done, [4] [5]. In this case, due to the large size of the tubular sections used in the bridge space frame design, access problems caused by the brace-chord intersection, and the requirement to move the robot to the node rather than jig a node in front of a fixed robot, it was not considered feasible to use a conventional robot. Hence, a major objective was the development of an automated welding system that could locate a pipe or node joint, locate the prepared gaps and automatically complete the required weld. The system had to be capable of adapting to variations in fit-up and alignment to ensure a high quality joint that satisfies structural quality requirements. Additionally, to cope with site conditions, the welding robot had to be small and easily assembled/disassembled by one or two semi-skilled operators, with single operator usage. The mechanised GMAW systems used for pipeline construction fulfil some of these requirements but they do not have the required flexibility to follow a complex tubular intersection, [6]. Hence, a prototype portable welding robot was designed to travel around the brace with sufficient degrees of freedom to follow the complex weld path. The carriage track is circular, as for pipeline welding. Therefore, to access all around the joint, a long axis parallel to the brace's longitudinal axis is required to hold the torch.

The prototype, shown in Figure 9, has been developed to meet the requirement of the fabrication process, highlighted from the field trial, and address the welding technology issues outlined above, [3]. It is driven using adaptive control software that is detailed in reference [7]. A screen shot of the software is shown in Figure 10. The detailed description of the hardware, welding technologies used and the control software is beyond the scope of this paper.

Figure 9. Prototype welding hardware for tubulare nodes

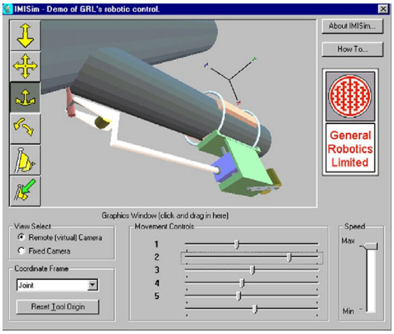

Figure 10. The interface of the adaptive software for the welding robot

4 The business process study

The construction industry suffers from inherent problems that must be overcome during every project with different parties being involved in the design, material supply, fabrication, transportation and erection stages. Moreover, the flow of information and knowledge tends to be in one direction only. Inevitably, problems occur and have to be solved that could have been avoided if identified earlier. The reason for this is simply that the party who could have addressed the particular issue had no knowledge of its occurrence – and probably insufficient expertise to have addressed it satisfactorily.

It is widely acknowledged that, in the construction industry, the decisions that have the greatest effect on the overall cost of a project occur during the conceptual design stage [8]. It is also acknowledged that the greatest efforts made to reduce the total cost occur during the fabrication and erection stages [9]. It would, however, be very difficult for the designer to appreciate and consider every potential problem the design may produce.

An examination of the processes involved in the design, fabrication and erection of a SPACES bridge has been carried out with the aim being to map a single business process. The business process is intended to effect strategies that will result in structurally sound and workable designs, by designing-out potential problems. This is done by proposing a good practice approach to the construction of SPACES bridges, to identify the parties involved in the process along with their responsibilities, and to identify goals for their tasks that may alleviate problems for other parties.

4.1 Modelling the business process

A successful analysis and modelling of a business process requires the application of a number of methods and techniques. These include: simplification of ‘no-value’ processes; elimination of ‘sink-holes’ where data are produced but never re-used; elimination of ‘re-work’ processes where duplication occurs; harmonisation of individual processes and tying them together taking into account their inter-dependencies; and re-engineering the overall process by identifying the goals, requirements and tasks and re-producing a new model which satisfy all these.

In this work, the processes involved in the total construction process have been mapped using information gathered from institutions and companies that have experience in the fields covered, including structural design, fabrication and erection of long span bridge structures, welding Circular Hollow Sections (CHS) and coping with the effects of welding and casting structural elements. The information incorporated observations of working practices and structured interviews.

Information with regards to workable geometries to address fabrication issues was also gathered from the field-trial fabrication described earlier. This allowed working practices to be examined, and for problems created by the fabrication process to be identified and solved at the design stage.

Having obtained sufficient information, a business process modelling software package has been used [10]. It uses decomposition diagrams, which allow processes to be broken down into their constituent tasks, and work and activity flow diagrams. The identified processes were drawn-up in a series of diagrams showing the parties involved with their responsibilities and tasks along with the associated flow of information and materials between them. Figure 11 shows the top-level process model, outlining the overall fabrication and erection process for SPACES bridges. More detailed processes have been modelled of the main activities that have influences on the interfaces between the various parties involved in the overall construction process in further diagrams [2].

4.2 Recommendation for a good-practice process

A 'good-practice' approach to the construction of the SPACES bridge is proposed which identifies goals for each of the critical tasks in order to alleviate problems for other parties and to ensure that the structure does not lose the cost effective advantages provided by the SPACES solution. The main goals and associated recommendations are given below:

4.3 Use of suitable bridge type

SPACES bridges are found to be competitive for viaduct bridges with spans in the range 50 – 100 m, so piers allowing spans within this range are preferable. Although spans outside this range might still be able to use this type of bridge deck, it is unlikely that it will competitive.

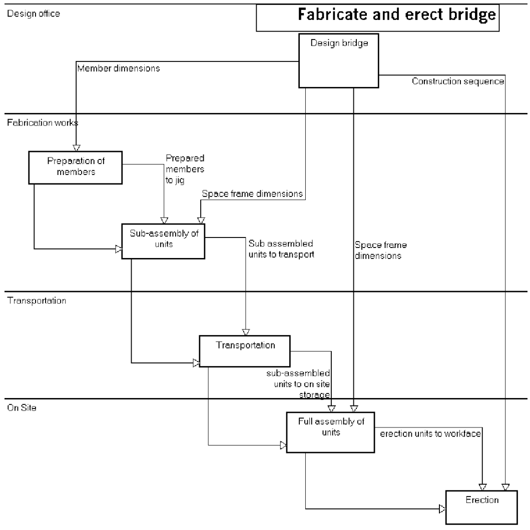

Figure 11. Process model showing the fabrication and erection of SPACES bridge decks

4.4 Efficient space geometry

Efficient space geometry from the structural point of view can be achieved through the use of appropriate span to depth ratios and the maximum length of structural elements between the nodes. An analysis of the structural performance of the SPACES bridge has resulted in the limiting values given in Tables 6 and 7 for span to depth ratios and a range of recommended elements lengths between the connecting nodes respectively [2].

Table 6. Recommended span to depth ratios

	Simply Supported	Continuous
Motorway Bridges	18-22	20-25
Rail Bridges	12 - 17	15 - 20
Pedestrian	18 - 22	20 - 25

Table 7. Recommended node spacing

Frame Member	Length between nodes
Chord	4 to 6 m
Inclined Brace Members	3 to 5 m
Horizontal Brace Members	4 to 6 m

Table 8. Recommended brace to chord diameter ratios

	Maximum	Minimum
Brace/Chord diameter ratio	0.6 if fabricated; 0.95 if node is cast	0.4
Chord/Inclined brace angle	60	50

4.5 Efficient use of material

The top and bottom chords are sized according to their relevant axial stresses calculated using moment and axial force equilibrium. It is recommended to use the minimum satisfactory section diameter within the range of standard chord wall thicknesses. It is also advisable to limit the maximum chord utilization ratio to 85% at the preliminary design stage, to allow for reduced joint capacity and consideration of local bending in chords because of welded brace elements.

The diagonal braces are sized so as to resist the inclined brace axial force arising from vertical shear at any point along the span ignoring any shear resistance contributions by the slab and the top and bottom chords. For reasons of economy, this is only done over the supports and at the quarter points in the span. The brace diameters are restricted to a minimum within the range of standard wall thicknesses. This is so to improve nodal conditioning, i.e. minimise the size of the brace footprint on the chord surface. Generally conditioning can adequately be achieved if the brace/chord diameter ratio is less than 0.6. The limits for brace to chord diameter ratios are given in Table 8.

4.6 Reduction of the risk of re-work

The possibility of having to re-work design solutions increases in areas where esoteric decisions have knock-on effects on later stages in the design process. This applies to much of the structural engineering decisions relating to member sizes and structural topology which have implications on fabrication issues, especially for tubular space structures. This is especially true when the processes of structural analysis and member sizing are separated from the process of connection detailing. Such a separation is a practice followed in many countries. The reasoning behind this practice is that fabricators might have their own specialist practices and would therefore prefer to specify the way connections are fabricated to meet a certain specified performance. It is a common misconception that the capacity check and detailing of connections for adequately sized structural members selected to withstand the forces on them is a straight-forward matter. The problem arises when the specified performance cannot be met given the constraints set for the member sizes and geometry. This means that re-design is often necessary to avoid complex reinforcing.

The risk of re-work can therefore be reduced by 1) considering the effects of member sizes and structural topology on the fabrication process and 2) the bringing together of all structural engineering processes. The first point is addressed earlier in the recommendation for a good-practice process. The second point is addressed by the use of an integrated structural design process that is embedded in a decision support software package and that is expanded-on later.

4.7 Minimisation of amount of welding

The SPACES system is economical in terms of material used within its competitive range. However, it is a fairly complex and costly system to fabricate. This is mainly due to welding and associated fabrication processes including jigging and handling. It is essential therefore to minimise the amount of welding. This can be achieved by minimising the number of nodes by maximising the cell spacing and by careful consideration of how the structure is divided into separate fabrication assemblies.

4.8 Provision of adequate access for jigging and welding

The provision of a structurally efficient geometry does not necessarily provide adequate access to enable efficient fabrication. The provision of adequate access space around the weld will impose constraints on the angles of the diagonal bracing and how far apart they are from each other. An analysis of the range of deck depths and cell spacing requires that the angle between the chord and the diagonal brace should be between 50º-60º in order to provide adequate access. In addition, the gap between the toes of the intersecting braces should at least be 50mm. This is to allow sufficient space for access during jigging and welding, even though structural design rules would allow much smaller gaps.

4.9 Facilitating the use of automatic welding

The recommendation is similar to the provision of adequate access except that the access space must take into account the size of the automatic-welding robot and the space required for its setting-up. An additional recommendation will be the provision of connection geometry and welding specification in a form compatible with the adapter software controlling the robot.

4.10 Assessment of implication on fabrication cost

A means of assessing the cost implication of design decisions on fabrication content should be provided. A cost model that would allow for the appraisal of the relative cost implication would be a valuable means of assessing the merits of different possible design solutions.

4.11 Assembly, jigging and welding

The work also brought to light issues that need to be considered during the selection of assembly sizes. The jigging process must be considered here along with transportation issues, the erection sequence and the delivery of steel. The splice joints should be positioned at a reasonable distance from the nodes for reasons of strength as well as access. These splice joints should, therefore, align with the delivered length of the chord sections so as to avoid any excessive cutting and welding. Assembly sizes must be optimised for jigging, welding and transportation (maximized for fabrication and erection and minimized for transportation).

4.12 Standardisation of detailing

Savings from improved fabrication efficiency due to repetitive work in most cases outweigh savings in the use of material. It is also recommended, therefore, that the node arrangements are as standardised as possible, thus reducing the fabrication time compared with having to fabricate many different node arrangements.

In certain cases, and where possible, the distance between the piers should be changed, with implication on clear span, in order to allow for the use of standardised cell size across the whole span.

4.13 Other good-practice issues

Guidance from the fabrication stage can also be introduced into the positioning of cast nodes. These nodes are cast from a die fabricated to the correct geometry; the members joining at such nodes are then welded to the cast node, as opposed to being joined directly to each other. Cast nodes have a higher fatigue life, and although they are about 5 times more expensive than welded nodes their use is advisable in locations of high stress fluctuation. This is as opposed to the alternative of not using them and as a result having to strengthen all the nodes in order to maintain standard detailing. The overall cost of construction for these two alternatives should be the deciding factor. Other guidelines have also been provided for material and welding inspections, cutting and preparation, jigging and assembly.

5 The decision support software

The mapping of the business process and the recommendations of 'good-practice' have identified goals and recommendations on how to achieve these goals. However, in a practical situation, effecting some of these recommendations can be daunting in the presence of complex 3D geometry and the many goals needed to be satisfied simultaneously.

The complex processes of design, fabrication and erection could benefit from decision support systems. Decision support systems normally refer to computer-based systems that make use of knowledge in the form of information, procedures (know-how) and decision rules supported with a reasoning mechanism. Such systems would typically apply some form of knowledge-management to assist in the decision making process. There is ample number of publications dealing with the historical development of these systems and the current state of the art, e.g. [11] and [12].

A decision-support software was developed for the purpose of facilitating the conduct of the proposed good practice. The experimental software has been developed using Object-oriented Programming in C++ and OpenGL™ (Open Graphic Library) for 3D graphical modelling. The software uses a single product model to represent concurrent views of the structure from the structural engineering point of view (frame analysis, connection analysis, and member design) and the fabrication point of view (welding specification, connection geometry, material quantities, etc.).

Figure 12 shows the hierarchical structure of the software. The software uses an interactive virtual reality environment. The core of the software is the Process Model, which controls all activities and communicates with the interface. The Process Model stores the data relating to structural design and fabrication parameters in the Integrated Product Model. The Process Model makes use of the Structural Analysis & Design Module and the Cost Model to perform calculations relating to the structural analysis of elements forming the structure, the design checks of structural members, the design checks of 3D tubular connections and the accumulation of material and fabrication costs. The Process Model also performs design critique by consulting the structures and the fabrication

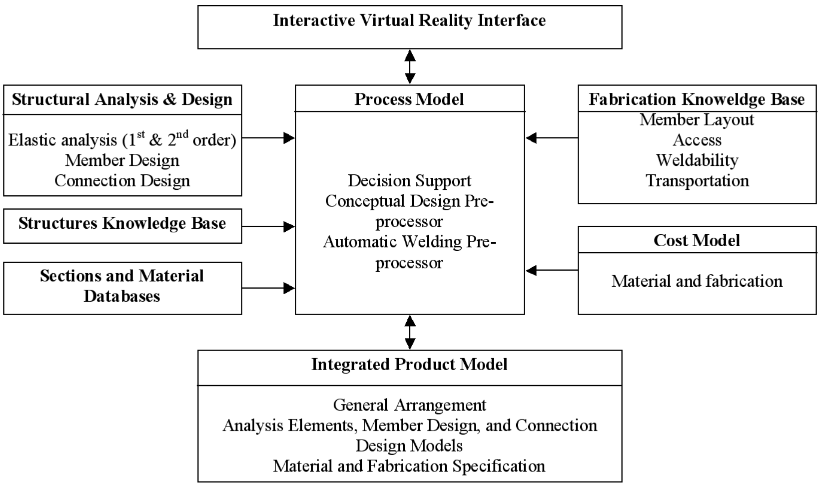

Figure 12. Hierarchical structure of the decision support system

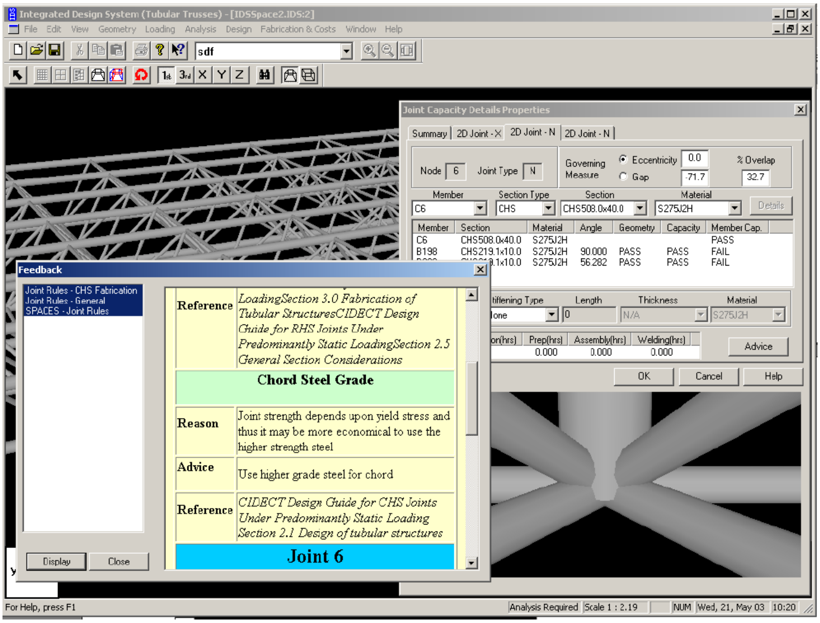

Figure 13. Checking of connection capacity

knowledge bases. The following summarizes the main aspects of the software, concentrating on that of the conceptual design.

5.1 Conceptual design pre-processor

Engineering rules of thumb and the recommendation of the good-practice have formed the basis for an automated generation of a workable conceptual design solution for a SPACES bridge. This is done using a pre-processor that applies the considerations of workable and cost effective cell spacing and structural efficiency. Knowing the required deck width and the minimum and maximum possible spans (pier positions), the cell spacing and the depth of the deck can be calculated along with the recommendation of optimum piers positions. This is done by maximising the cell spacing so as to reduce the amount of welding, and by providing a structurally adequate deck depth so as to produce brace lengths and angles that allow for sufficient access and weldability while maintaining standardised connection details. The pre-processor then determines the preliminary sizing of the three main structural members (top and bottom chords and the bracing) based on the limiting moment and shear forces resulting from the application of nominal highway loading. The solution satisfies a set of constraints drawn from the recommendations of the 'good-practice" approach outlined earlier. As a result, the pre-processor creates as a result a complete product model. This includes an analysis model (nodes, elements, and restraints) and a design model (individual members, section sizes and properties, along with joint details and geometries).

5.2 Integrated structural functions

Having completed the preliminary design, a detailed design process can be carried out using the product model produced by the pre-processor. The product model has built-in integrity links between its components, i.e. members, joints, etc. allowing for the effects of changes to be seen in the overall model. Through the use of this model, a great deal of tedious work can be taken out of the design process, allowing the designer to concentrate on creativity, specification and testing of design solution for structural, fabrication and erection issues. The structural analysis is undertaken using an integrated analysis engine. This uses a stiffness method approach and compiles into a 'plug-in' dynamic link library. The analysis engine models the member end connections, by applying different stiffnesses these can be designed as encastré, pinned, sprung and so on. Similar to structural analysis, detailed structural member and connection designs are performed using design modules providing feedback on the performance of the members and connections. The feedback is given in terms of pass/fail ratios for the full range of design checks and qualitatively by consulting design rules. Figure 13 shows a typical output. The analysis and design operations are applied directly to the product model. The fact that the product model itself is used, as opposed to a representation of it, means that the integrity of the whole solution is maintained where changes in aspect is propagated to the others.

5.3 3D Visualisation

Using the OpenGL™ technology, the system produces a virtual solid model of the structure. This enables designers to better examine their design choices by 'seeing' the structure as it is going to be built. Figure 2 shows an example of the 3D model with an overall view of the space-frame, Figure 14 shows a close up view of a typical SPACES joint.

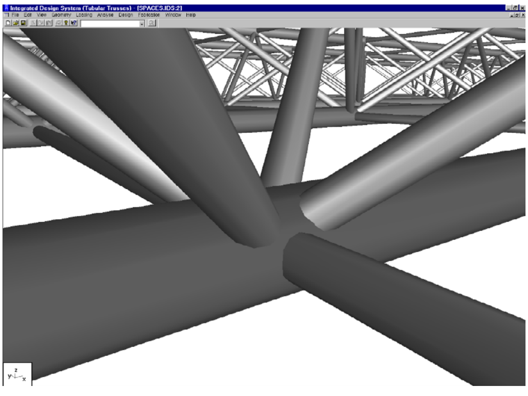

Figure 14. A close-up view of a typical SPACES joint

5.4 Cost modelling

A process cost model has been developed and integrated with the system. The model estimates the cost of materials and individual fabrication operations using cost functions; the model is based on earlier work [13, [14]. For the welding operation, the cost is based, among other factors, on the deposition rate that can be achieved using a specific welding technique. Using a specified SPACES structure (member sizes, geometry, etc.) the cost is instantly available and it is therefore possible to dynamically cost the structure as it is being modified. Having the ability to create multiple instances of a spaces structure, it is also possible to quantify the relative effect on costs for various alternative schemes. With the ability to specify automatic or manual welding for every weld at any specific joint, comparative costs are available that compare the efficiencies of automatic, semi-automatic and manual welding. A preliminary investigation into the relative cost saving that can be achieved using the semi-automatic welding equipment versus manual welding was carried out using a design for the Øreson Crossing Bridge as a case study. It was concluded that savings of 35% on the labour cost of welding could be achieved. This makes 4% of the total cost of the steel structure.

5.5 The knowledge-based system

A knowledge-based system is a tool that can help designers to critically look at decisions made, by providing embedded expertise in the form of rules of thumb. A set of rules has been compiled in a knowledge base which can be 'consulted' using an 'advice engine'. As a result of this, designs can be checked for compliance. Advice on further action can be obtained in case of non-compliance. The rules that have been included in the knowledge-base deal with aspects such as optimum depth, longitudinal and transverse cell spacing, width and length of assembly units, positioning of splices and cast nodes, appropriate use of automated welding and practical joint detailing

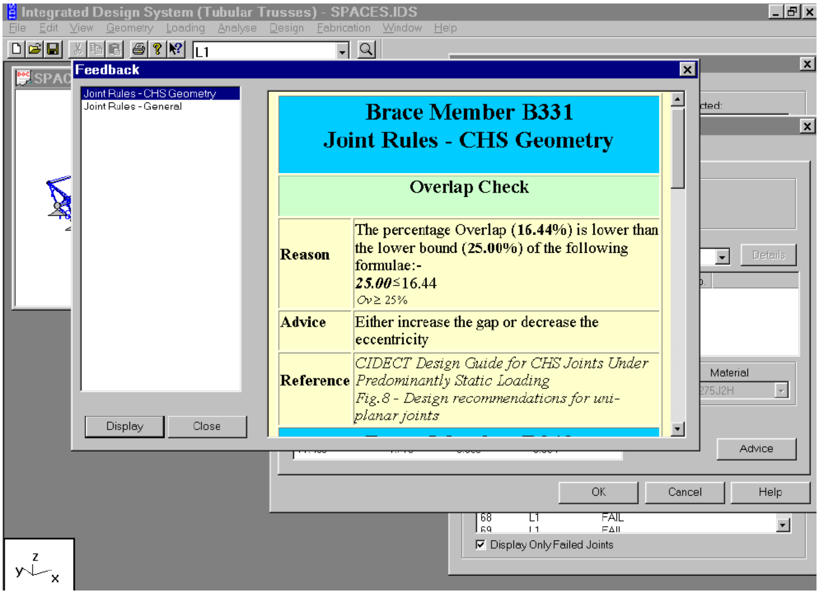

Figure 15. Typical advice feed-back on structural design

(gaps for welding and access). Figure 15 illustrates some of the feedback from the advice engine.

5.6 Interface to automatic welding

An export facility provides an interface to the adaptive welding control software used to control the automatic welding robot [15]. This is a means for transferring all geometrical data, member sizes and welding specification at each node to a pre-determined format that can be read by the adaptive software. Using this facility it is possible to use this information for the set-up of the robot at each node without having to re-input information node by node.

This section outlined the main operations of the software that implements a process that allows for the generation of conceptual design solutions to bridges made with tubular space structures. The software integrates all aspects of structural engineering closely linked to good-practice fabrication process. Operating the software, it is possible to produce workable solutions that are likely to produce savings and results in better quality structures. The software is still experimental and has not yet been used in the field. The likely benefits cannot therefore be substantiated at this stage. However, the software has been evaluated using case studies and the indications are that it could result in significant savings, not least in the time taken to produce workable designs.

6 Summary and conclusions

The problems inherent in the construction process have been addressed in this paper. More specifically, those problems occurring in the fabrication and erection of welded tubular steel bridge structures have been investigated, using the SPACES system as a case study. Although SPACES bridges are highly efficient in terms of material, the study has shown that this efficiency is balanced by fabrication and erection phases that are expensive and potentially problematic. This is especially true for the amount and complexity of the welding involved.

A field trial of the fabrication of an assembly of a SPACES bridge has been carried out at a collaborating steel fabrication. Dimensional analysis of the assembled prototype structure was used to model the assembly process and assess the fabrication and construction tolerances that could be achieved on a complete bridge structure. A mathematical model of the nodal connection coupled with the measured tolerances has been used to specify the parameters that effective automatic-welding equipment will need to satisfy.

A prototype automated welding equipment controlled by adaptive software was developed and trialed. The prototype was designed to satisfy the specifications resulted from the field-trial. The prototype is shown to improve the productivity of the welding process of tubular nodes. More details of this aspect of the work can be obtained from the referenced work.

This paper concentrated on the study into the business processes involved in the construction of SPACES bridges and how such a process can be re-engineered to improve their competitiveness and facilitate more automated means for welding. The business processes involved in the construction of these bridges have been studied and a re-engineered model for them has been suggested. A list of key recommendations for the conceptual design, fabrication, transportation and erection practices has been suggested. This has formed the basis of a 'good-practice' approach to the design of these types of structures.

The proposed good-practice has been incorporated into an integrated structural design and fabrication software. The software facilitates the conduct of a construction-led design process and supports welding automation. Using the software, the designer is able to quickly generate a good-practice compliant design solution that adheres to the proposed recommendations and reduces down-stream problems.

Acknowledgements

The work was funded by the EPSRC under the IMI-LINK programme; reference: GR/M22468.

The field trial fabrication was carried out at the specialist bridge contractor Cleveland Bridge UK Ltd.

The study into the business process was carried out with a large amount of assistance from David Dawson and John Cadei of MSP-Maunsell, David Taylor of Cleveland Bridge UK Ltd and Rick Legatt of The Welding Institute, by providing the benefits of their experience.

The work undertaken to develop the automatic-welding system and the adaptive welding control software have be carried out by Cranfield University (led by S Blackman) and University College London (led by A Greig) respectively.

The project also received financial support from Corus Tubes Ltd.

REFERENCES

[1] Churchman, A. E. and Cadei, M. C. (1998). "SPACES: Structural behaviour and characteristics of a composite tubular steel space frame bridge deck system", Tubular Structures VIII (Eds: Choo & Van der Vegte), publ. Balkema, Rotterdam, pp 81 – 90.

[2] Whitehead, A. S. (2001). "An investigation into the fabrication and erection process of SPACES structures", MPhil Thesis, The University of Nottingham, UK.

[3] Blackman, S. A., Rivas, S., Greig, A., Tizani, W., Whitehead, A. S. and Bertaso, D. (2000). "Automated FCAW for Tubular Structures", Proceedings of the International Conference on Advances in Welding Technology 2000, Gas Metal Arc Welding for the 21st Century, pp. 269-278, Orlando, USA, 6-8 December, 2000.

[4] Huissoon, J. P., Kerr, H. W., Bedi, S., Weckman, D. C., and Stefanuk, W. P. (1992). "Design of an Integrated Robotic Welding System", Proceedings, 3rd International Conference on Trends in Welding Research, Gatlinburg, TN, 1-5 June 1992, ISBN 0-87170-476-5, pp.915-919

[5] Lauridsen, J. K., Madsen, O., Holm, H., Hafsteinsson, I. and Boelskifte, J. (1995). “Control of a one degree of freedom workpiece manipulator for welding the root bead in pipe branches”, JOM-7 Proceedings, International Conference on the Joining of Materials, Helsingor, Denmark, 31 May-2 June 1995 ISBN 87-89582-03-9 pp.526-535.
[6] Blackman, S. A. and Dorling, D. V. (1999). “Mechanised GMAW for Transmission Pipelines”, Pipeline Welding and Technology Conference, The International Conference on Advances in Welding Technology ‘99, Galveston, USA, 26-28 October 1999.
[7] Greig, A. R., Rivas, S., Blackman, S., and Tizani, W. (2001). ‘Welding Automation in Space Frame Bridge Construction’, *Journal of computer-aided civil and infrastructure engineering,* Vol. 16, No. 3 pp. 188 – 199, May 2001. Eurocode 3: “Design guide for circular hollow sections (CHS) joints under predominantly static loading”, VERLAG TUV Rheinland,Germany, 1991.
[8] Tizani, W. (1996). “Re-engineering the design process using I.T.”, in Knowledge-based systems in structural engineering: current development and future trends, (editor C J Anumba), Institution of Structural Engineers, London, pp 43-51. (ISBN 1874 266 29 8)
[9] Miles, J., Foley, A., and Moore, L., 2000, “Metaphors and Cost Significance in a Conceptual Design Decision Support System”, Proceedings of CIT2000 – The CIB-W78, IABSE, EG-SEA-AI International Conference on Construction Information Technology: 640 – 649. Reykjavik, Iceland.
[10] Sterling Software. (1999). “Business Process Modelling with Cool::Biz – Student Guide”, Sterling Software, USA.
[11] Turban, E. and Aronson, J. E. (1998). “Decision Support and Intelligent Systems”, (5th edition) Upper Saddle River, N.J., Prentice-Hall Inc., 1998.
[12] Holsapple, C. W. and Whinston, A. B. (1996). “Decision Support Systems: A Knowledge Based Approach”, Minneapolis, MN., West Publishing Inc., 1996.
[13] Nethercot, D. A., Tizani, W., and Smith, N. J. (2001). “Integrated design of tubular steelwork”, The Structural Engineer, Vol 79, No. 3, pp. 25-29, Institution of Structural Engineers. 6 Feb 2001.
[14] Tizani, W., Nethercot, D. A., Davies, G., Smith, N. J., and McCarthy, T. J. (1996), “Object-oriented fabrication cost model for the economic appraisal of tubular truss design”, Advances in Engineering software, Civil-Comp Limited and Elsevier Science Limited, Vol. 27, pp 11-20. (ISSN S0965-9978(96))
[15] Rivas, S., Greig, A. R., Blackman, S. and Tizani, W. (1999). “Robotic Welding of Tubular Nodes”, 16th IAARC/IFAC/IEEE International Symposium on Automation and Robotics in Construction, pp. 603 – 607, Madrid, Spain.