A PROTOTYPE OF KNOWLEDGE BASED EXPERT SYSTEM FOR DESIGN OF STRUCTURAL STEEL JOINTS

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ABSTRACT

The paper deals with a prototype of a knowledge based expert system developed for the design of structural steel joints. The graphical user interface and the possibilities of the system are described. At the moment expert knowledge in the system is preliminary but the knowledge aquisition in the field from expert in the domains of design, fabrication and erection is just going on. A demo version of the system can be run in the URL http://www.ce.tut.fi/~heinisuo/eng_fst.html in the internet.

INTRODUCTION

Most parts of costs of a structural steel project are fixed during the early stages of design process. The design of structural joints is of the main importance in steel skeletons, and to be done in a cost effective manner, many factors are needed: a comprehensive knowledge of fabrication, transportation, erection, mechanics and a plenty of time and other resources, such as software, hardware and know-how. Usually, all those are not available. A real working design process should be organized so that the starting point is a geometrical model of the structure (here steel skeleton with joints) and after that the structural analysis and the dimensioning is done with the required iteration (Mikkola, 1985), (Heinisuo et al 1991). When defining the geometrical model the knowledge of fabrication, transportation and erection is needed in order to find an economical solution. The demands of cost effectivity and structural stiffness are often in conflict.

There exist general algorithms for the generation of three dimensional analysis models from geometrical models (Boender et al, 1994), but these algorithms lead to too heavy analysis models in practice. Articifial intelligence applications exist which can be used to construct general analysis models from geometrical models. An integrated architecture for the structural analysis of mechanical structures has been proposed (Remondini et al, 1996). The structural analysis can be done (following the previous reference) not only using FEM but also using strength of material approach or boundary element method or other such methods. There exists a novel knowledge-based assistance for finite element modeling (Turkiyyah, Fenves, 1996), which can be used not only for the selection but for the *construction* of the analysis model from the geometrical model. These are general models and the expert knowledge dealing especially with steel structures is not available in those systems.

There exist expert systems developed for the design of structural steel joints. A British system (Tizani et al, 1994) is limited to welded joints of tubular truss joints. A Dutch system (DeGelder et al, 1995) is based on the design process in which the joint detailing is done by the fabricator of the skeleton and the design is done *after* the analysis, using the force distribution given by the structural designer. By this system the iteration needed in the case the joint detailing has an effect on the force distribution (e.g. semi-rigid joints) is almost impossible to perform. Both these expert systems are reviewed in detail in (Heinisuo & Hyvärinen, 1995).

A knowlegde based expert system (KBES) called FST-EXPERT for the design of steel skeletons has been proposed (Heinisuo, Hyvärinen, 1996). The KBES is used for the *selection* of the analysis model from the propositions stored in the database. This system tends to have limited coverage (Turkiyyah & Fenves, 1996) but it seems to work well in the problems considered. Moreover, in the future the system may be applied repeatedly on a joint, and thus the analysis model will be constructed. The KBES is used mainly for the selection of suitable joints for the steel skeleton taking into account the mechanical and economical aspects. Following this, the KBES system proposes suitable joint parameters and the proper analysis models. The user can choose the model using the KBES taking into account the need of the accuracy of the result (0D, 1D, 2D, 3D, local or global models) and resources of the project (time, software and hardware capacities, know-how etc).

This paper deals with the present stage of the system. The KBES is used for three tasks:

1. Selection of suitable joint types for a case under consideration

2. Proposition of default values for the joint parameters

3. Selection of possible analysis models for the joints

The expert knowledge collected from the field experts in relevant domains and from the literature are taken into account when performing the three tasks. So far, the expert knowledge installed into the system is preliminary. The knowledge aquisition in the field is just going on. The suitability factors to help the decision making are calculated using a standard method of Certainty Factors. An example is shown in this paper to demonstrate the possibilities of the system. The demo version of the system can be run in the URL http://www.ce.tut.fi/~heinisuo/eng_fst.html in the internet. Prototype links from the KBES to analysis (Heinisuo, Hyvärinen, 1996) and to cost estimation are made starting from the CAD model of the skeleton. The data exhange between applications is done using STEP-files (ISO 10303-21) and product data model of steel skeleton (Hyvärinen 1996), which is written in EXPRESS-language (ISO 10303-11).

JOINT TYPE SELECTION

To select the type of a joint is a task which requires expertise of several aspects, e.g. constructional and economical aspects. Therefore, a knowledge based expert system which contains these aspects is a powerful tool for the selection.

Expert knowledge is represented in tables (Figure 2). A table contains expert knowledge of an aspect. A row of the table has knowledge of an individual joint type. A column of the table is a property of the aspect which the table represents. The knowledge is expressed as suitability factors (from 0 to 1).

For the time being there are three tables: static, fabrication and erection. The static table describes the static behaviour, force transfer ability, of the joint type. In Figure 2 there are only three properties in the static table, but for the more complete result a bigger set of properties has to be included: bending moment in two directions, shear force in two directions, axial force, torsional moment and bimoment. In the fabrication table there are suitability factors of the joint according to each fabricator. Thus, the number of columns corresponds the number of fabricators. The factor of the joint type represents the suitability for the manufacturing technology of the fabricator. The contents of the erection table is equivalent to that of the fabrication table.

static

	M	V	N
	0.5	0.9	0.2
fst301	0.2	0.9	0.4
fst302	0.1	0.8	0.4
fst303	0.1	0.6	0.4
fst304	0.2	0.3	0.4
fst305	0.7	0.8	0.8
fst306	0.8	0.8	0.9
fst307	0.9	0.95	0.95

fabrication

	fab1	fab2	fab3
	0.4	0.9	0.3
fst301	0.82	0.7	0.7
fst302	0.9	0.8	0.8
fst303	0.85	0.7	0.7
fst304	0.8	0.6	0.5
fst305	0.8	0.4	0.7
fst306	0.79	0.3	0.8
fst307	0.5	0.3	0.7

erection

	erec1	erec2	erec3
	0.5	0.2	0.3
fst301	0.99	0.9	1.0
fst302	0.85	0.4	0.8
fst303	0.8	0.4	0.7
fst304	0.6	0.8	0.6
fst305	0.7	0.6	0.5
fst306	0.69	0.5	0.6
fst307	0.66	0.6	0.5

Figure 2. An example of static, fabrication and erection tables.

The user has a possibility to edit the contents of tables. Both the joint types and the properties may be added or removed. New tables may also be added, e.g. for maintenance. These operations are allowed only for so-called super user, because editing of the expert knowledge is involved.

An end user can set the weights of the tables and the properties. By means of these weights the end user is able to emphasize those aspects (tables) and properties which are important in the project under consideration. The value 0 as the weight of a table indicates that this table must not be taken into account. On the other hand the value 1 indicates the importance of the table. The weight of a property may vary from -1 to 1. E.g. in the static table the value -1 is given to the force which must not be transferred, the value 1 to the force which has to be transferred and the value 0 if the force is irrelevant.

In order to find the most suitable joint type, the unsuitability factors of all the joint types are calculated according to the following procedure. The unsuitability factor of the joint type when considering a property is calculated using equations

$$PF_{i,j} = (1 - s_{i,j}) \cdot w_j , \qquad w_j > 0, \tag{1 a}$$

$$PF_{i,j} = -s_{i,j} \cdot w_j , \qquad w_j < 0, \tag{1 b}$$

where

$PF_{i,j}$ = unsuitability factor when considering a property,
i = joint type index,
j = property index,
$s_{i,j}$ = suitability factor of a joint,
w_j = weight of a property.

The unsuitability factor of the joint type when considering an aspect is

$$TF_{i,j} = TF_{i,j-1} + (1 - TF_{i,j-1}) \cdot PF_{i,j} , \tag{2}$$

where

$TF_{i,j}$ = unsuitability factor when properties 1 to j have been considered,
$TF_{i,j-1}$ = unsuitability factor when properties 1 to j-1 have been considered, if j=0 then $TF_{i,j-1}=0$.

If $TF_{i,j}=1$, the joint is rejected. The final unsuitability of the joint type is

$$CF_{i,t} = CF_{i,t-1} + (1 - CF_{i,t-1}) \cdot TF_{i,t} \cdot w_t \quad , \tag{3}$$

where

$CF_{i,t}$ = unsuitability factor when tables 1 to t have been considered,
$CF_{i,t-1}$ = unsuitability factor when tables 1 to t-1 have been considered, if t=0 then $CF_{i,t-1}=0$,
t = table index,
$TF_{i,t}$ = unsuitability factor of table t,
w_t = weight of the table t.

The suitability of the joint type is expressed as

$$SF_i = 1 - CF_i , \tag{4}$$

where

SF_i = suitability factor of the joint type i,
CF_i = unsuitability factor of the joint type i when all the tables have been considered, i.e. CF_i is the last result of Eq. 3.

Undefined $s_{i,j}$ is interpreted as the value 0.5, while undefined w_j and w_t are interpreted as the value 0 (Heinisuo & Hyvärinen 1996, p. 79). The system proposes the joint type with the best suitability factor, but the end user can choose the joint type he/she prefers.

The joint types for the whole structure are selected one by one. Due to this, there is possibility to select the joint types so that the whole structure or a part of it becomes a mechanism. Fortunately, advanced FEM software give a warning about this. But there also exist FEM software which don't react to the mechanism in any particular manner. Thus, some expertise is required when selecting the joint types.

JOINT PARAMETERS

After the joint type selection there is still an important task to determine the values of the joint parameters. For each joint in the system, a set of parameters is specified to represent its characteristics. Dozens of parameters can be found in a joint and defining their values is a task which requires significant amount of work (Figure 3). Some of the parameters can be calculated automatically on the basis of the geometry, e.g. the cutting angle of the beam. In the pilot implementation, the values of the joint parameters are generated by joint macros which are developed in CAD environment used.

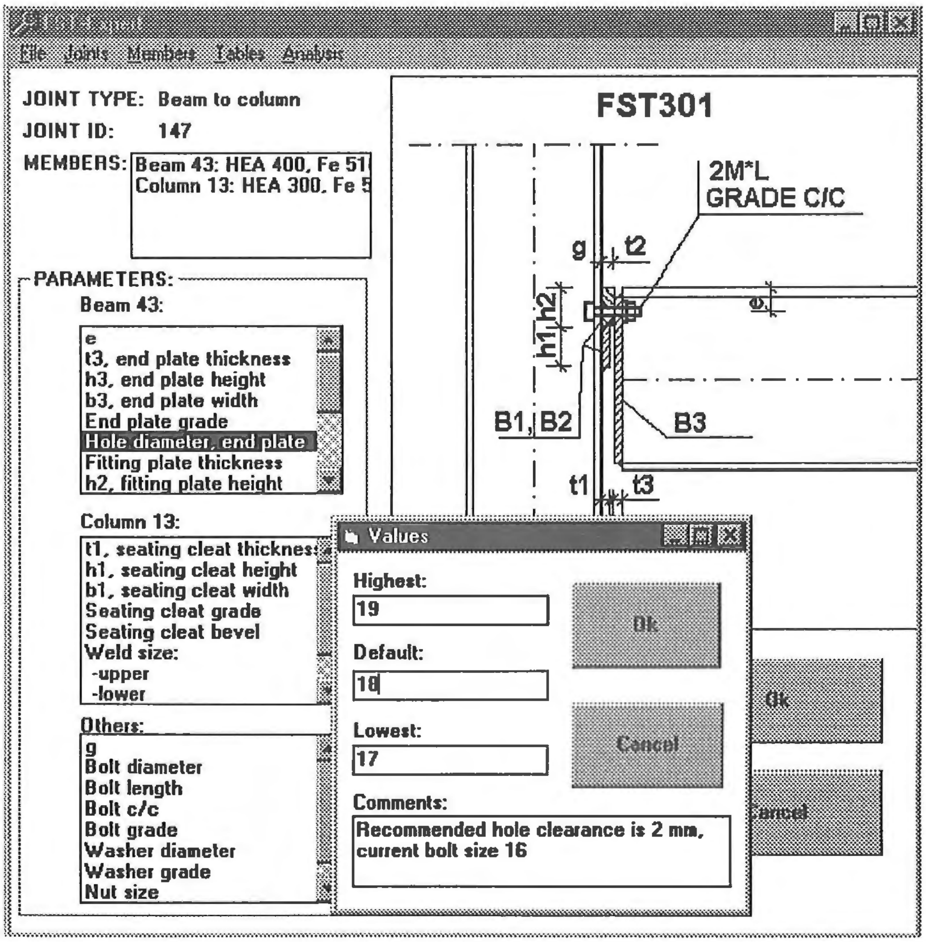

Figure 3. An example of values of joint parameters.

Expert knowledge is needed in determination of the values of the parameters. The system proposes some reasonable default values. Also the highest and lowest bounds for the values of the parameters are presented if necessary. There exist hard or soft constraints. The hard ones are derived from geometrical limitations or from codes and standards, e.g. the distance of the hole from the edge of the web. The soft ones are based on the common practice and experience, e.g. the grade of bolts. For these constraints the system offers explanations including expert knowledge (Figure 3).

When the values to the joint parameters have been given, the geometry of the steel skeleton is complete and the product model (FST-model, Hyvärinen, 1996) can be updated concerning the joint data. The joint macros to update the model in the pilot environment are under development in the project.

STRUCTURAL ANALYSIS MODEL

The next stage in the design of process is the structural analysis. The analysis model for the structural analysis is selected by a procedure corresponding to that of the joint type selection. At the present there are two beam models and a plate model which can be selected for the example joint FST301 (Figure 4).

The aspects which affect to the selection of the model are presented as tables (Figure 5). The static table illustrates how the analysis models are able to describe the static behaviour of joints. The resources which are available for the designer are presented in the resource table.

The suitability factors are calculated in the same way as in the selection of joint type. The appropriate model is selected and the product model for the structural analysis is generated (Heinisuo & Hyvärinen, 1996, p. 81). The product model is a STEP-file and the analysis can be performed using any FEM software which is available (examples, see Heinisuo & Hyvärinen, 1996).

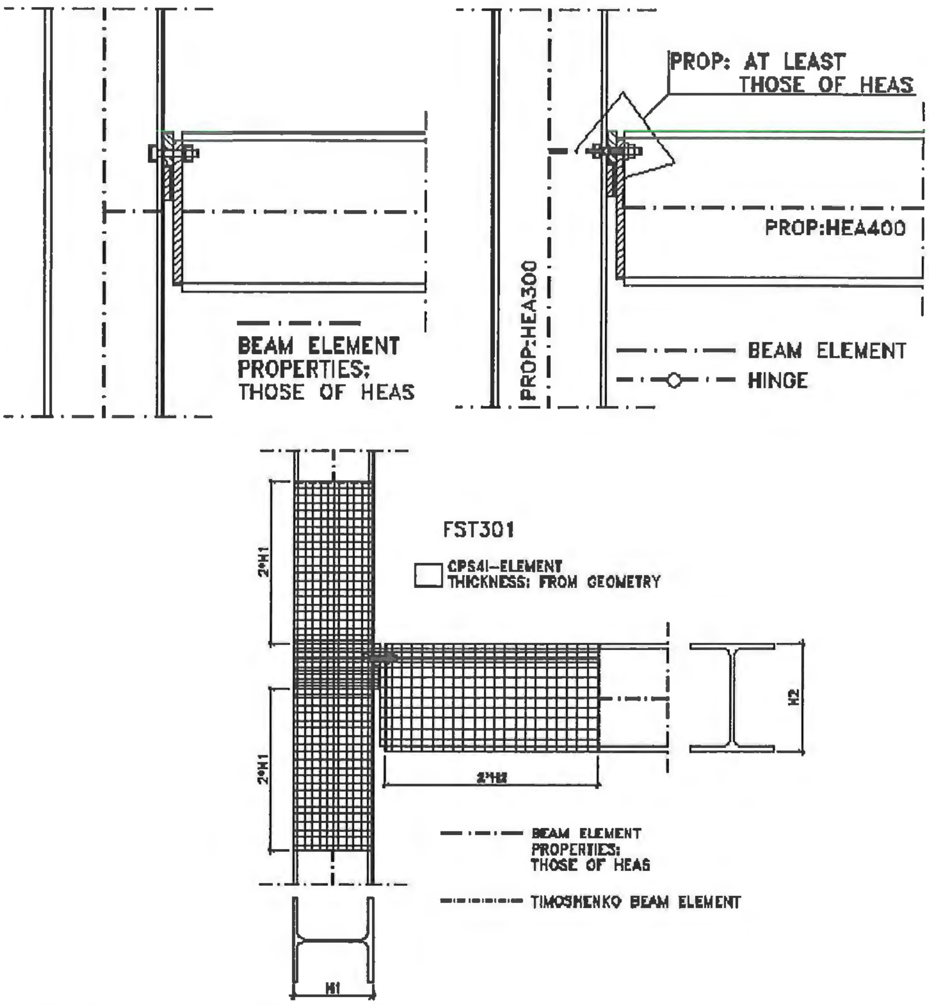

Figure 5. Analysis models of a beam to column joint.

	N1	V1	V2	M1	M2	rotation	stress_cons
	0.8	1.0	0.0	0.1	0.0	0.7	0.0
model1	0.7	0.7	0.0	0.4	0.0	0.3	0.3
model2	0.8	0.9	0.0	0.85	0.0	0.6	0.5
model3	0.8	0.9	0.0	0.9	0.0	0.8	0.9

	DOF	software1	software2	knowhow
	0.8	1.0	0.0	1.0
model1	1.0	1.0	1.0	1.0
model2	0.8	1.0	1.0	0.9
model3	0.2	0.0	1.0	0.3

Figure 5. Static table and resource table for the selection of structural analysis model. DOF=degree of freedom.

COST ANALYSIS

Traditionally the costs of the steel skeleton have been calculated using the weight of the skeleton as a basis. The total cost is achieved by multiplying the weight by the average rate per ton. The method leads to minimizing the weight which can result in more costly design, e.g. more complicated connections and additional stiffeners.

If the costs are divided into its components, several benefits are achieved (Watson et al 1996, pp. 2-3):

- the method is more reliable and the result more accurate,
- the continuity of approach from initial project costing through to fabricator's detailed costing is provided,
- the elements which have the most significant effect on the final cost can be pointed out,
- the cost of contract variation is determined reliably.

A set of components is proposed by Heinisuo 1995, p. 29: design, material supply, fabrication, coating, transportation, erection and fire protection. Each of them can be divided into more detailed shares, but so far we are satisfied with the less detailed division (so called shallow knowledge, also appearing in the KBES). E.g. material supply costs are given as rate per unit length and cost of bar cutting as a cost of a cut. The total cost is calculated by finding the amount or the number of all elements in the product model, multiplying them by unit prices and summing them all up. An example of this kind of cost estimation can be found in (Heinisuo, Hyvärinen, 1995b).

This kind of cost estimation is possible if we have a product model and a cost aggregation form of the skeleton. The most important point is that there exist corresponding elements in both the product model and in the cost aggregation form.

KNOWLEDGE ACQUISITION

The proper expert knowledge is a fundamental condition for a knowledge based expert system. As a part of this research project the shallow knowledge acquisition is carried out. The deep knowledge will be acquired in future researches. The experts to which acquisition sheets were sent represent three domains in the steel construction: design, fabrication and erection. The designers were asked for suitability factors with respect to seven force transfer properties. The fabricators and the erectors were asked to give the suitability in man hours. This value is converted into the suitability factor when inserting the knowledge into the system.

PRESENT STATE OF RESEARCH PROJECT

The selection of the joint type, the selection of the analysis model and the cost analysis stand ready. First joint macros are being developed. The expert knowledge acquisition is going on and first responses have been received.

AN EXAMPLE

To demonstrate the selection of the joint type a simple case is considered. The task is to select the joint type for a beam to column joint. There are 20 candidates available in the database for this case (I-beam to I-column, see the reference to the WWW-page above). In the first case let's assume that the ability to transfer the bending moment is important. So the weight of the bending moment is set to the value 1.0 (Figure 6). In the second case the moment is inessential and its weight is set to the value 0.0. The weights in the other tables are kept the same and they are not shown. In the first case the system proposes the joint FST319 and in the second case the joint FST301 (Figure 8). The suitability factors of the two joints are shown in the Figure 7.

	M	V	N
	1.0	1.0	0.5
fst301	0.2	0.9	0.4
fst319	0.3	0.85	0.9

	M	V	N
	0.8	1.0	0.6
fst301	0.2	0.9	0.4
fst319	0.3	0.85	0.9

Figure 6. The partial static tables in two cases.

JOINT	SUITABILITY
fst319	0.454651
fst301	0.223194

JOINT	SUITABILITY
fst301	0.522369
fst319	0.493279

Figure 7. The suitability factors of FST301 and FST319 in two cases.

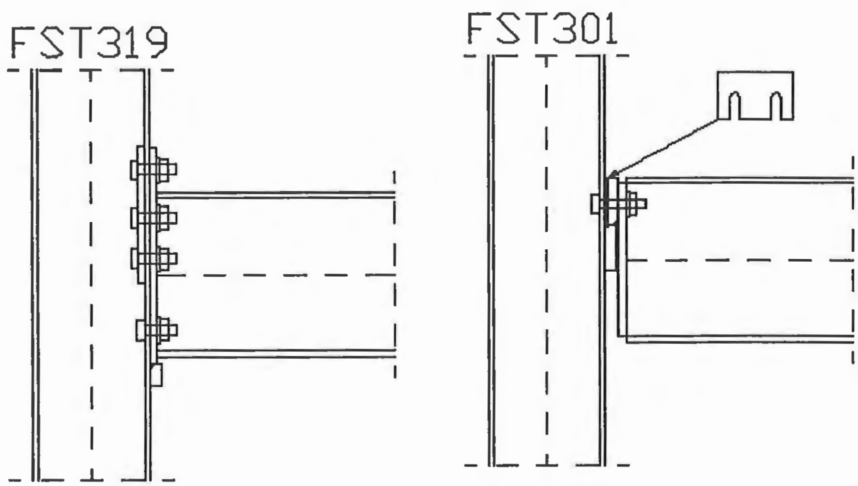

Figure 8. The proposed joint types in the example.

CONCLUSIONS

The knowledge based expert system for the design of steel structures and especially the joints is described in the paper. The solutions proposed by the system depend on the expert knowledge installed into the system. At the moment the knowledge is shallow in the KBES concerning especially the fabrication and the erection of the skeleton, but the knowledge aquisition in the field is just going on in the project. The system and its applications (e.g. the cost estimation) can apply very deep knowledge due to exactness of the product model and the details available in the cost aggregation form. Nowadays, the structural analysis programs can also handle very accurate models with reasonable resources.

A considerable part of the design process of steel skeletons can be done by the computer applying the KBES and the neutral data files developed in the project. The use of neutral STEP-files means that we are working in an open i.e., hardware and software independent, environment. The design process starts from the CAD-model of the skeleton (without joints). After that, the KBES proposes joint types and joint parameters and local analysis models for the joints (and also bars between joints, this part is not handled in this paper). The next step in the design process is to update the product models and to analyze the skeleton and after that the cost estimation and necessary iterations can be done. Then the product model of the steel skeleton can be sent to the fabricator or any other organization which needs it.

So far, links to dimensioning and mapping from the product model (FST-model) to the models used by fabricators are missing from the system. The joint macros are the cornerstones of the implementation system. The library of those must be wider than today and a tool to make new macros is needed in order to use the system in practical projects.

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REFERENCES

Boender, E., Bronsvoort, W. F. & Post, F. H. 1994. Finite-element Mesh Generation from Contructive-solid-geometry Models. Computer-Aided Design, Vol. 26, Num. 5, pp. 379-392.

De Gelder, J. T., Steenhuis, C. M. & Huijsing, A. P. 1995. Knowledge Based Connection Design in Steel Structures. Knowledge Support Systems in Civil Engineering. 1995 Bergamo, Italy. AIBSE Colloquium., pp. 75-85.

Heinisuo, M., Möttönen, A., Paloniemi, T. & Nevalainen, P. 1991. Automatic Design of Steel Frames in a CAD-system. Proceedings of the 4th Finnish Mechanics Days, 5-6 June 1991. Lappeenranta, Lappeenranta University of Technology, pp. 197-204.

Heinisuo, M. 1995. Teräsrungon kustannuksista. Teräsrakenne, 18, 4, pp. 29-32. (In Finnish).

Heinisuo, M. & Hyvärinen, J. 1995a. Expert Systems for Design of Steel Structures, Part 4: Kirjallisuuskatsaus keinoälysovellutuksiin teräsrakenteiden suunnittelussa. Tampere, Tampereen teknillinen korkeakoulu, Raportti 18, 56 pp. (In Finnish).

Heinisuo, M. & Hyvärinen, J. 1995b. Hierarchical Aggregation Form of Steel Skeleton. Proceedings of ECPPM '94 - The First European Conference on Product and Process Modelling in the Building Industry, Dredsen, Germany, 5-7 October 1995. A.A. Balkema, pp. 147-154.

Heinisuo, M. & Hyvärinen, J. 1996. Knowledge Based Approach to the Design of Structural Steel Joints. Information Processing in Civil & Structural Engineering Design, 14th-16th August 1996, Glasgow, Scotland. Civil-Comp Ltd, pp. 75-85.

Hyvärinen, J. 1996. Expert Systems for Design of Steel Structures. Licenciate Thesis. Tampere University of Technology, Department of Civil Engineering. (In preparation).

ISO 10303-11. 1994. Industrial automation systems and integration - Product data representation and exchange - Part 11: Description Methods: The EXPRESS language reference manual. International Organisation for Standardisation, Geneva. 208 pp.

ISO 10303-21. 1994. Industrial automation systems and integration - Product data representation and exchange - Part 21: Implementation Methods: Clear text encoding of the exchange structure. International Organisation for Standardisation, Geneva. 57 pp.

Mikkola, M. 1985. Computer Aided Design of Wood Trusses Using Nail Plates. Proceedings of CIVIL-COM 85, Vol. 1, CIVIL-COMP-PRESS, Edinburg, pp. 149-154.

Remondini, L., Leon, J. C. & Trompette, P. 1996. Towards an Integrated Architecture for the Structural Analysis of Mechanical Structures. Information Processing in Civil and Structural Engineering Design, CIVIL-COMP, Edinburg, pp. 65-73.

Tizani, W. M. K., Davies, G., Nethercot, D. A. & Smith, N. J. 1994. Construction-led Design of Tubular Trusses Using a Cost Model: Knowledge Acquisition and Representation. Tubular Structures IV, Eds. Grundy, Holgate&Wong, Balkema, Rotterdam, pp. 411-416.

Turkiyyah, G. M. & Fenves, S. J. 1996. Knowledge-Based Assistance for Finite-Element Modeling. IEEE INTELLIGENT SYSTEMS & THEIR APPLICATIONS, Vol. 11, Num. 3, pp. 23-32.

Watson, K. B., Dallas, S. & van der Kreek, N. 1996. Costing of Steelwork from Feasibility through to Completion. Steel Construction, 30, 2, pp. 2-47.

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