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Design Optimisation of FRP Universal Connectors

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SUMMARY

There has been an increased demand for developing special connecting elements for pultruded fibre reinforced plastics (PFRP) structures. The first prototype of a moulded fibre reinforced plastic (FRP) universal connector (UC) was presented to the industry in previous work. The merit of this connector was proven through a full-scale testing program for PFRP beam-to-column connections. In order to develop a series of FRP connections with high structural performance and the lowest possible associated cost, design optimisation techniques must be utilised. For this reason, a design optimisation study on a FRP universal connector was conducted. In evaluating the structural performance of each UC design, finite element analysis was employed. The main objective of the study is to develop an optimum design for the UC by maximising its load carrying capacity and minimising the stress concentration at the critical locations. In order to minimize the number of design variables required for producing the optimum UC, the Taguchi statistical method for quality control was incorporated in this study. In this method, statistically planned experiments are used to identify the settings of the UC design parameters that reduce performance variation. Among the different parameters selected in the study are the UC geometry, composite lay-up, and thickness of the various elements comprising the connector. The results of the analysis indicated that the UC wall thickness, the addition of diagonal webs, and the orientation of the fibres in the webs improve the stiffness significantly. Other design recommendations and conclusions are also presented.

INTRODUCTION

Background

Connections are often the governing elements that play a major role in controlling the serviceability and ultimate strength, as well as being responsible for the majority of the dissipation capability of PFRP frame structures. For this reason, careful design of the connecting elements is paramount to improving the design and construction of PFRP structures. Due to the absence of appropriate composite connectors, most of PFRP structures are designed using a hinged connection

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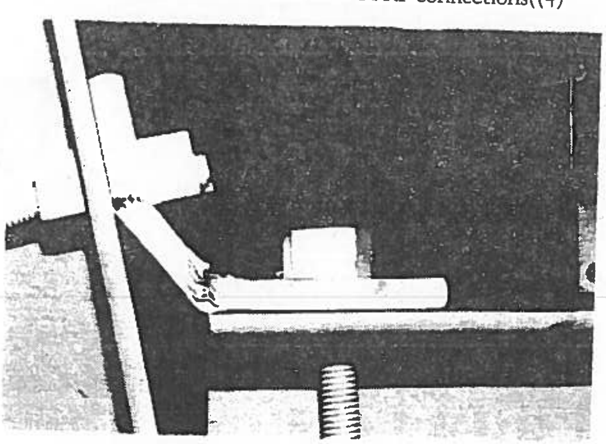
assumption[1]. In addition, most of the available connection design details recommended by the manufacturers[2,3], are duplicates of steel framing connections. The approach of "mimicking" metal connection details neglects the anisotropic nature of the material and will generally result in unsafe and uneconomical overall design. Figure 1 shows the typical ultimate failure of "steel-like" PFRP connections[4]. In addition, no appropriate design procedures for PFRP connections are available for frame connections. The establishment of reliable connection design procedures requires extensive full-scale research and development studies on different PFRP connections. The need of these experimental studies is to fully understand the performance of these connections under different loading conditions.

Several full-scale studies on the performance of PFRP frame connections were performed in the past few years. In these studies, the majority of the tested specimens have utilised PFRP connecting elements that were commercially produced and were not intended specifically for connecting purposes[5,6]. This was an appropriate approach to demonstrate the deficiency of existing connection details and the influence of their performance on the overall performance of frame structures. To overcome this problem, a different approach for connecting PFRP structural elements is needed to ensure the prosperity and the efficiency and safe use of this material. This approach is to develop a special connecting element or system using a mixture of the past experience, available research and design data, and knowledge of the anisotropic behaviour of the composite materials. The design criteria of the these connecting elements include proper fibre orientation, ease of erection and duplication, geometrical flexibility of use for different structural connections, and maximising both the overall connection stiffness and ultimate capacity.

Figure 1 typical failure of "steel-like" PFRP connections((4)



PFRP Connections Related Work

In the past few years, several research studies have been conducted in the area of characterising the structural behaviour of pultruded composite connections[5,7,8]. The available research works can be classified in two interrelated categories.

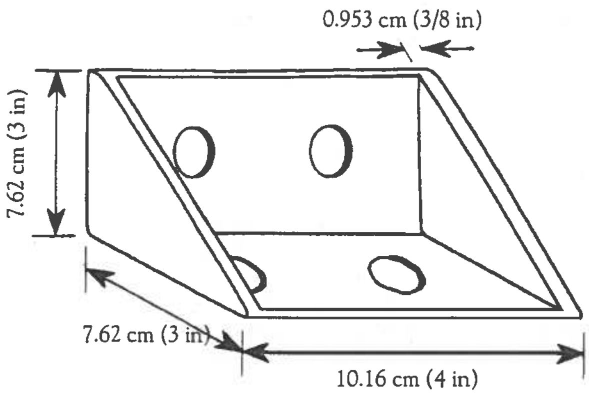
Studies on the Mechanical Characterisation of PFRP Joints and Fasteners

Chapter 4 of the ASCE Structural Plastics Design Manual[9], contains valuable information about mechanical joints, fasteners and adhesives for different types of structural plastics. Matthews[10], discussed the mechanical behaviour and design methods for single bolt joints in double shear. A review of strength characteristics of FRP adhesively bonded joint was discussed[11]. Austin[12], presented a brief summary of a report on Connections for Structural Plastics. This report is a part of Phase One of the ASCE manual for structural plastics connections which is sponsored by the Structural Composites and Plastics Committee. Love and Bisarnsin[8] conducted an experimental investigation on fasteners used for industrial building applications. Lately, Sotiropoulos and GangaRao[13], completed a comprehensive review on connectors for FRP members. In this report, design equations for bolted and adhesive-bonded joints were presented.

Full-Scale Connections Research Studies

In 1984, an experimental study was conducted on a PFRP column-to-base connection using both composite and metal connecting elements. For PFRP frame structures, a comprehensive theoretical and experimental study on the short and long-term behaviour of PFRP frame structures was conducted by Mosallam[5]. In this work, the effect of connections' details and their semi-rigid behaviour were studied. Furthermore, the impact of the connection flexibility on the creep performance of PFRP structures was also discussed. Based in this work, Bank, Mosallam and Gonsior[14], conducted theoretical and experimental investigations on the performance of PFRP connections. Bank and Mosallam[16], presented results of an experimental

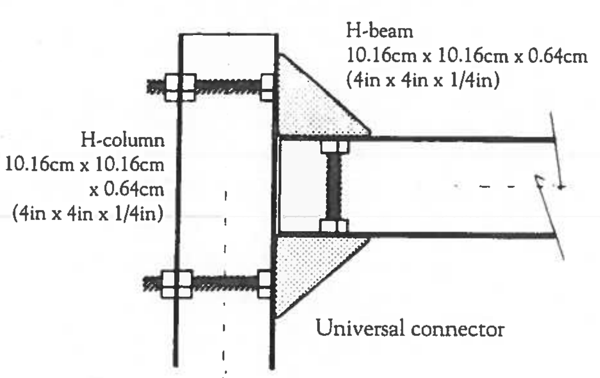
Figure 2 Modified universal connector



study for three different PFRP connection details. For each connection, the rotational stiffness was calculated from the corresponding experimental moment-rotation curve (M/θ). In 1992, Bank, Mosallam and McCoy[16] extended this work by performing a study on different types of PFRP connections using existing structural profiles as connecting elements. Although some of the connections' details presented in their work were impractical, the approach was appropriate to demonstrate the importance of including the anisotropic nature of the material in connection design.

As a first step towards the correct design path, Mosallam[7], has developed a customised connecting element that was designed to achieve strength, stiffness and geometrical flexibility and suitability for connecting a large variety of open and closed-web PFRP structural profiles. For the latter reason, the connecting element was referred to as the Universal Connector or UC (see Figures 2 and 4). The lay-up and structural details are given[4]. The UC element can be used for the majority

Figure 3 UC beam-to-column connection detail[17]



of PFRP connection details for joining different structural shapes, e.g. exterior and interior beam-to-column connections, column-base connections, continuous beam connections, beam-to-girder connections, and others. A comprehensive discussion of the application of UC for different PFRP frame connection details is presented by Mosallam[1].

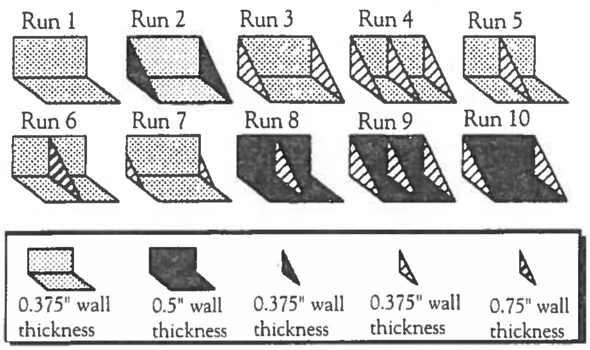
To verify the structural efficiency of this connecting element and to demonstrate the gain of using correct structural details for PFRP connecting elements, Mosallam, Abdelhamid, and Conway[17] performed a full-scale testing program on both the static and dynamic performance for three details of PFRP beam-to-column UC connections (type (v), (vi), (vii)) Test results indicated that an increase of about 300% in the connection ultimate moment of type (vii) was achieved over the corresponding ultimate capacity of available connection detail (type v). In addition, the average stiffness of the same connection was about 25 times the other connections (type (v), (vi)). Recently, a new detail for flexible beam-to-column exterior UC connection was presented by Zahr, Hill, and Morgan[18]. In this study, failure mode and stiffness characteristics of this connection were reported. A finite element analysis on the performance of universal connectors was also conducted by Bedewi, Mosallam and Goldstein[19].

Based on the results obtained from the above research program, two important conclusions can be identified:

1. In general, there is a structural deficiency in the majority of off-the-shelf open-web PFRP profiles(4). This is due to the discontinuity of the reinforcements between the web and flanges. Figure 3 shows the under-reinforced inverted triangle at the web/flange junction of most of the "off-the-shelf" PFRP open-web profiles.
2. There is an urgent call for removing improper steel-like isotropic connection details from the available manufacturer's design guides[2], and replace these details with acceptable, structurally sound connection details.

The objective of this study is to develop a UC design that produces maximum connection stiffness. In this study, an optimisation procedure is described which employs the finite element techniques in evaluating each design.

Figure 4 Connector configurations analysed using the FEM



ANALYTICAL PROCEDURES

The Universal Connector

The Universal Connector adopted in this study was developed by the first author, and several prototypes of this connector were manufactured using resin transfer moulding process (RTM). The UC was fabricated from E-glass/vinyl ester composition. Figure 2 shows a typical configuration of the modified UC. Figure 3 demonstrates the application of the UC in beam-to-column connections(7). Based on the encouraging experimental results of the structural performance of the UC, the need for developing the most efficient form of this prototype was essential to transfer this technology to the industry.

Given a set of bolt patterns and a prescribed loading condition, the finite element analysis was performed for each UC design. The aim of this analysis is to optimise the connection geometry by varying fibre orientation, number and location of webs, and material thickness. The original base line UC was based on an equal angle configuration.

Finite Element Analysis procedures

Solution Formulation

The finite element method (FEM) divides the structure under study into a number of simple shapes that share adjacent grid points. A stiffness matrix is constructed based on the type, material, and geometry of the elements used. In this analysis, plate elements were chosen due to the connector geometry and type of loading conditions. Each element is assigned material properties depending on the type of material being modelled. In the case of PFRP, the material is orthotropic, therefore the following four independent constants need to be specified: moduli of elasticity in both directions (E_x and E_y inplane shear modulus (G), and Poisson's ratio in any one of the two directions (note that $\nu_y E_x = \nu_x E_y$). The individual stiffness elements are assembled into a global stiffness matrix utilising the fact that adjacent elements share grid points. Boundary conditions are applied by restricting various degrees of freedom. The stiffness matrix is then reduced and numerically inverted to determine the final displacements. These displacements are substituted into the element formulations to obtain the stress distribution.

FEM Model of the Universal Connector

A model of the beam-to-column connection was constructed by maintaining both beam and column as rigid members and modelling the connector with finite elements. An eccentric load (P) was then applied on the beam at a distance (e) of 38.10 cm (15 in.) from the bolt location to produce a flexural load (M = P.e). Given that the model is linear-plastic, the relation between moment and deflection is linear and therefore scaling of the results is possible. For the baseline analysis, a force of 220 N (100 lbs.) was applied at the aforementioned location. Two boundary conditions were applied:

i) full constraint of translation and rotation at the column bolt locations,
ii) vertical constraint of the horizontal section of the connector

The material properties used to define the orthotropic elements are as follows:

- modulus of elasticity in the direction (x): Ex = 17.237 (GPa (2.5×10^6 psi)
- modulus of elasticity in direction (y): Ey = 5.516 GPa (0.8×10^6 psi)
- shear modulus: G = 4.0 GPa (0.58×10^6 psi)
- Poisson's ratio in direction (x): $\nu_x = 0.30$

This data is based on E-glass/vinyl ester composition with a volume fraction of 45%.

DESIGN OPTIMIZATION PROCEDURE

The traditional approach of developing an efficient design of an existing structural element using FEM involves several runs for different models. For each model, a comparison between the existing and the

Table 1 Design Factors

Factor	Description	Level 1	Level 2
A	Web fibre orientation	-45/+45	0/90
B	Full outboard webs	None	Yes
C	Partial outboard webs	None	Yes
D	Inboard webs	None	0.953 cm
E	Inboard webs	None	1.905 cm
F	Bracket wall thickness	0.953 cm	1.270 cm

improved case is compared until a satisfactory design is obtained. This approach may require a large number of iteration cycles including modification to the new model, analysis and comparison to the previous ones. The number of iterations depends, mainly, on the knowledge level of the engineer and the complexity of the FE model, especially when the number of design variables is large. In addition, when a satisfactory model is obtained, the possibility of better improvement will still be questionable if slight modifications are introduced. This is due to the lack of independent evaluation of each contributing design parameter. Taguchi[20], introduced an alternative parametric design technique for this purpose. The advantage of this method is its ability to evaluate a number of design parameters simultaneously, and determining their contributions independently on the final design.

The Taguchi Method

The Taguchi Method for Statistical Quality Control proposes a novel approach of using statistically planned experiments for parameter design. In this method, variables affecting the performance characteristics of the product (the universal connector in our case) are classified into the following two categories.

Table 2 FEM combination matrix

Bracket Configuration	Factor Levels A	B	C	D	E	F	Signal-to-Noise Ratio
1	1	1	1	1	1	1	5.26
2	2	2	1	1	1	1	26.69
3	1	2	1	1	1	1	29.43
4	1	2	1	2	1	1	38.14
5	1	1	1	2	1	1	30.48
6	1	1	1	1	2	1	33.28
7	1	1	2	1	1	1	20.78
8	1	1	1	2	1	2	35.99
9	1	2	1	2	1	2	41.25
10	1	2	1	1	1	2	35.89

1. Design Parameters are the product parameters whose nominal settings can be selected by the specialised engineer. These parameters define the product design specification.
2. Noise Sources are all variables that cause deviation of the performance characteristics from their target values.

The objective of this method is to identify the settings of design parameters with minimum noise factors effect on the performance characteristics. In this method two matrices need to be constructured. First, the design parameter matrix which specifies the test setting of design parameters. The columns of this matrix represent the design parameters, while the rows represent different combinations of test settings. Second, the noise factor matrix specifying the test levels of noise. The columns of this matrix represent the noise factors, and the rows represent the different combinations of noise levels. The Taguchi method for Statistical Quality Control is described in detail by Taguchi[20].

The use of this approach for design optimisation was developed originally by Quinlan[21]. This systematic technique is based on extracting meaningful global information from a solution set composed of a large number of data combinations by observing the behaviour of a limited set within the original space. In the context of this study, the objective is to find the optimal connector design by running a limited number of finite element scenarios, while in reality, there exists a large number of combinations of the design factors under investigation. After selecting the limited data set, a performance index such as signal-to-noise ratio (S_n) (in the context of statistical analysis) is constructed from the physical data. In our case, this data was chosen to be the displacements. Trends in the performance index are then observed and quantitatively analysed to construct some meaningful conclusions regarding the design factors.

Results of Optimisation Analysis

The six universal connector design factors considered in this analysis are listed in Table 1. Finite element models were constructed from several combinations of these factors. Deflection data at different critical locations on the UC were extracted for further evaluation. Figure 4 shows the ten configurations selected as the sample data set and which were analysed using FEM. For each case, the magnitude and location of the maximum deflection were observed. Deflections in the other connector geometries occurring at the same location were tabulated. For the ten configurations analysed here, five maximum deflection locations were identified. A deflection signal-to-noise ratio was calculated for each configuration using the following expression:

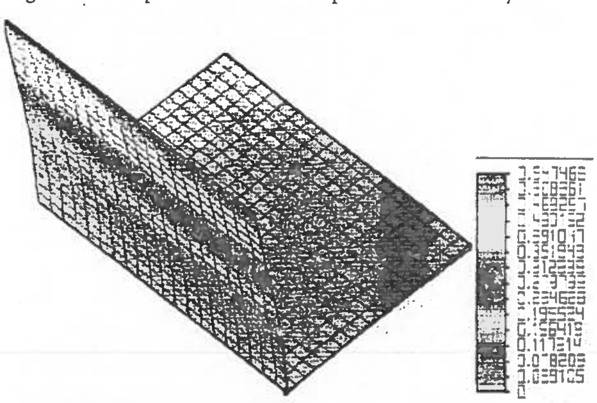
$$S_n = 10 \log\left\{\frac{\delta_1^2 + \delta 2^2 + \delta 2^2 + \delta 4^2 + \delta 5^2}{5}\right\} \quad (1)$$

where δ_i is the deflection at point i on the connector, and S_n is the signal-to-noise ratio in dB. Table 2 lists the FEM combination matrix with the resulting S_n calculations. The maximum deflection in the FEM analysis ranged from 0.024 cm (0.0094 in.) for configuration (9) to 1.37 cm (0.54 in.) for configuration (1). An example of the output from the finite element analysis is shown in Figure 5.

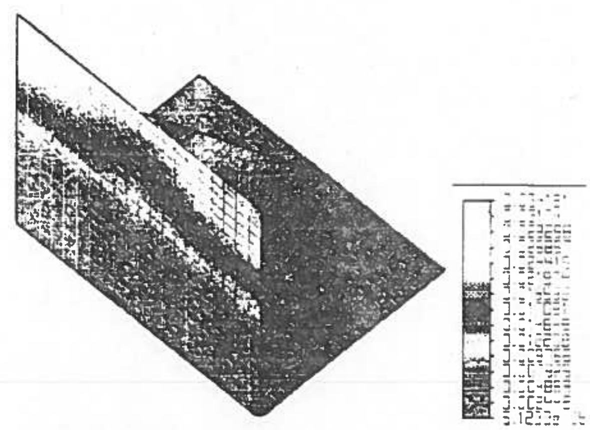
RESULTS AND DISCUSSION

The signal-to-noise ratio is an indication of the contribution of a given factor has on the performance index. By numerically combining the contributions of each individual factor for all the connector configurations, an overall performance indicator is obtained. This is achieved by averaging the Level 1 contributions for each connector configuration separate from Level 2 contributions, and constructing a list as shown in Table 3. This data gives a clear indication of the relative effect each design factor has on the overall stiffness performance of the connector. The data is better displayed in Figures 6 and 7. The data is interpreted by noting that a decreasing slope indicates a reduction in performance and that the higher the magnitude of the slope, the more significant the effect is. For a clearer presentation of results, a normalised graph (Figure 7) was obtained by shifting the Level S_n value to zero of Figure 6, thus maintaining a common starting point for the six design factors. Figure 8 shows

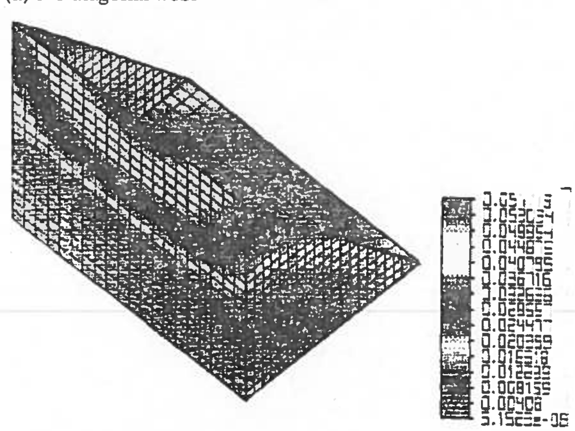
Figure 5 Examples of deflection output from FEM analysis



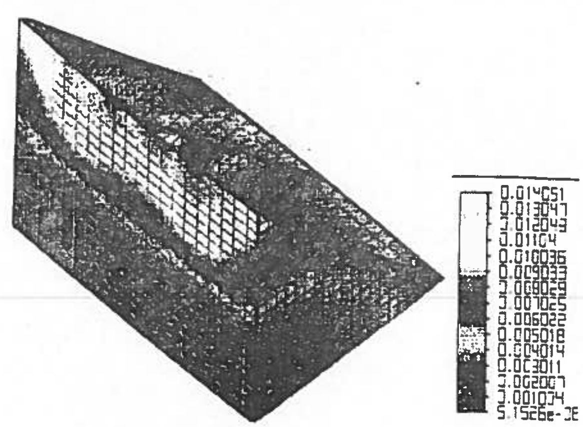
(a) No diagonal webs



(b) Central diagonal web



(c) Two outboard diagonal webs



(d) Three diagonal webs

Table 3 Stiffness contribution factors

	A	B	C	D	E	F
Level 1	30.05	25.16	30.71	25.22	29.32	26.29
Level 2	26.69	34.28	20.78	36.46	33.28	37.71
L2 - L1	-3.37	9.12	-9.93	11.24	3.96	11.42

the different curves for the displacements for several nodes at incremental distances along the middle of the connector for different design configurations. In this graph, the term "current" refers to run 1, with no diagonal web(s). The impact of using diagonal webs is clearly shown in this figure. By observing the trends of the curves in Figures 6, 7, and 8 and the contribution factors in Table 3, the following conclusions can be made:

1. Adding diagonal webs to the open flange (angle-like) connector increases the stiffness significantly.
2. A single inboard diagonal web has the same effect on the overall stiffness as double outboard diagonal webs; however, an experimental verification is needed to determine the effect of this design parameter on the moment-rotation (M/θ) characteristics of PFRP connections.
3. The stiffness is improved by orienting the diagonal web fibres in the ±45 direction.
4. Partial outboard diagonal webs degrade the stiffness significantly.
5. The UC wall thickness has the highest effect on connection stiffness.
6. The 3-web combination offers the highest rigidity, however, the same levels can be achieved with a thicker UC and a subset of webs.
7. Increasing the inboard diagonal web thickness has minimal effect on overall stiffness of the UC.

Figure 6 Contribution factors for the two design levels

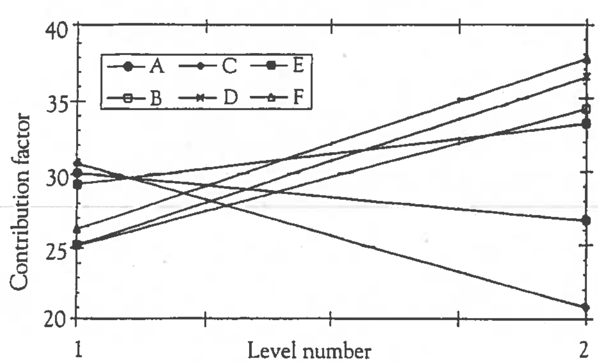
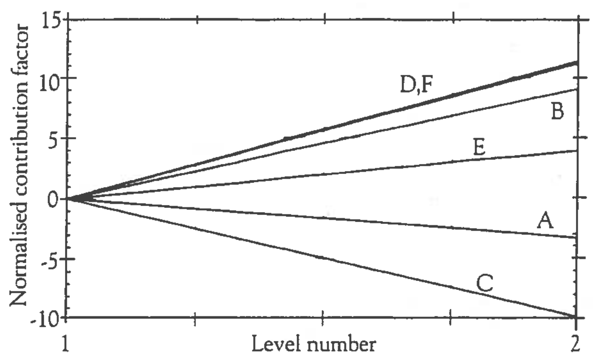
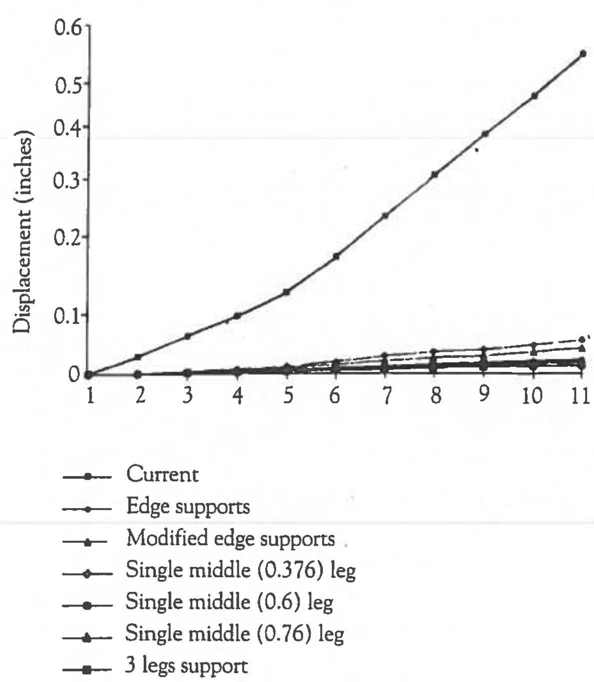


Figure 7 Normalised contribution factors for the two design levels



These observations give a clear direction in the design of the connector from a functional standpoint. However other factors that need to be addressed are manufacturing feasibility and cost. An ideal connector would have one inboard or two outboard diagonal webs, all with ±45 degree lay-up, with a 1.27 cm bracket wall thickness. The trade-off in fabrication and cost would affect factors such as three webs versus thicker UC, etc. Furthermore, some laboratory tests need to be performed to determine the M/θ values, which in effect will reduce the UC configuration design options.

Figure 8 The relative displacements along the middle of the connectors for different design configurations



CONCLUSIONS

A procedure for optimising the design of a beam-to-column universal connector is presented based on the Taguchi approach. Factors such as fibre orientation, wall thickness, and web location, number, and size were considered in the trade-off analysis. The results indicate that wall thickness has the most significant effect on overall thickness. Furthermore, the analysis indicates that while it is important to have webs in the connector, two outboard diagonal webs have the same overall effect as one inboard web. Finally, it is recommended that an experimental verification program on the performance of the modified UC be performed to determine the connection performance through M/θ experimental curves. This is specially important to resolve the effect of the web locations, which influences the economic aspects of manufacturing the UC.

APPENDIX 1 (SI UNITS)

1 Pound = 4.448 Newton
1 Kip-inch = 112.9 N-m
1 inch = 0.0254 Meter
1 psi = 6.895 kPa

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