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ALTERNATIVE/INNOVATIVE STRUCTRUAL CONCEPTS FOR OFFSHORE TOPSIDE COMPOSITE STRUCTURES

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ALTERNATIVE/INNOVATIVE STRUCTURAL CONCEPTS FOR OFFSHORE TOPSIDE COMPOSITE STRUCTURES

by

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Alternative/Innovative Structural Concepts for Offshore Topside Composite Structures

ABSTRACT

The present paper deals with innovative designs to be applied to composite structures in the topside area of an offshore platform. In the first part of this study, the currently applied concepts are described outlining advantages and disadvantages of each one. Also some innovations on the design and manufacturing of topside composite structures are presented.

The second part of this paper is devoted to the design of a composite flare boom, taking a steel structure as a reference. A comparison in terms of weight and cost is carried out. Special attention has been paid to the design and analysis of connections between chords and transverse braces. This is due to the fact that these parts are critical from both points of view stress concentrations and manufacturing complexity.

INTRODUCTION

Currently topside structures are made out of steel. However, the poor weld quality, the low fatigue strength of steel and the need to design large metallic surfaces (with the correspondent increase of wind loads), have led to failures, fatigue crackings and expensive maintenance operations. One alternative, which is innovative and efficient in terms of weight, cost, mechanical behavior and maintenance, consists of implementing composite materials.

Designing a topside structure with organic-matrix composite materials can be considered a challenge. The list of disadvantages and advantages of this material system compared to the standard one used in steel topside structures, which is carbon steel, are the following:

COMPOSITE MATERIALS FOR OFFSHORE OPERATIONS - 3

Alternative/Innovative Structural Concepts for Offshore Topside Composite Structures

Antonio Miravete[1]

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ABSTRACT

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The second part of this paper is devoted to the design of a composite flare boom, taking a steel structure as a reference. A comparison in terms of weight and cost is carried out. Special attention has been paid to the design and analysis of connections between chords and transverse braces. This is due to the fact that these parts are critical from both points of view stress concentrations and manufacturing complexity.

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Table 1. - Disadvantages and advantages of organic matrix composite materials with respect to the steel.

Disadvantages of organic-matrix composite materials compared to carbon steel	**Advantages of organic-matrix composite materials compared to carbon steel**
Higher cost of raw materials	Higher Mechanical Strength
Lower High Temperature Resistance	Lower Maintenance Costs
Lower Stiffness	Lightweight structure
More difficult to perform joints: welding is not possible	Molding Manufacturing Process

It is obvious that the cost of the composite topside structure must be competitive with the standard carbon steel. This is definitively one of the toughest requirements since the cost of the raw materials in this last case is very low. All carbon steel topside structures must be painted or coated due to the limitations of metallic materials (corrosion and high temperature resistance). According to the data available, the aluminum coating, which is considered as one of the most efficient coating in terms of maintenance and price, increases the cost about 30%.

The fire resistance is also another key issue. Several methods are available to meet this requirement. Ceramic coating is a promising alternative since it is very efficient in terms of heat isolation and the cost is very low, as long as this coating is not designed to bear any mechanical load. This issue will not be addressed in this paper.

The stiffness is a critical factor in terms of mechanical behavior; since low-cost organic matrix composite materials are several times less stiff that carbon steel. In order to overcome this problem, an optimization process will be carried out: the geometry of the structure, the material system, the typology of the material used, and finally the joints will be optimized in terms of cost and mechanical requirements. Needless to say the analysis must be very accurate and that design and manufacturing must be totally compatible, feasibility being an important matter in this project.

Finally, it is important to emphasize that a successful design of a topside composite structure in terms of cost and mechanical requirements would imply not only a reduction of the topside structure mass, but also a new concept for other primary topside structures, with the correspondent advantages of massive reduction of weight in such an important area. According to the present scheme, an innovative concept will be proposed. Apart from traditional composite processes like pultrusion, other recent techniques will be incorporated in this project. Nowadays, there are a number of textile technologies, which are very convenient for the construction of preforms to be used in R.T.M. pieces.

These techniques are the following:

- Braiding
- Stitching
- Knitting
- Weaving

The braiding scheme is shown in Figure 1.

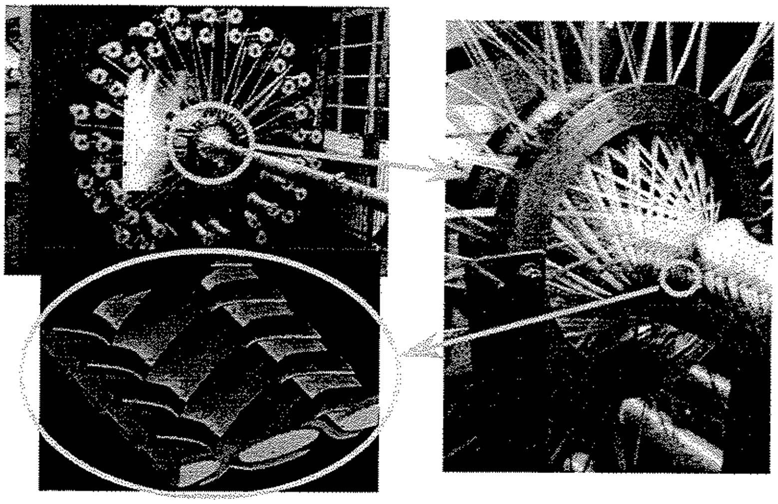

Figure 1. - Scheme of the braiding process and micro mechanical modeling.

Another technology available and quite promising for topside concepts is the warp knitting (Figure 2).

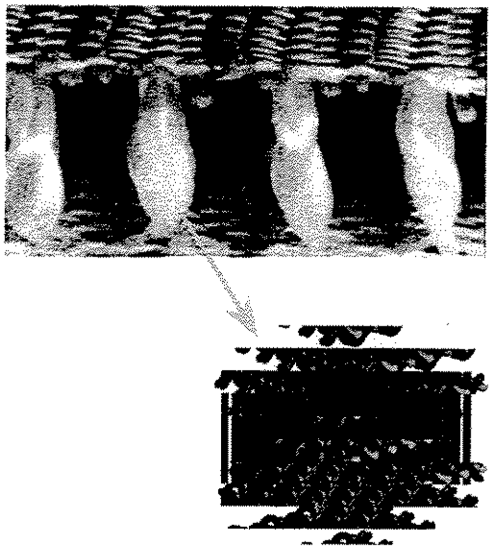

Figure 2. - Scheme of the warp knitting process and micro mechanical modeling.

REVIEW OF CURRENT CONCEPTS

Introduction

Five structural concepts will be described in this part. All of them are based on pultruded structures since pultrusion is currently the only manufacturing process present in the area of non-aeronautical structural applications. Though R.T.M. and other processes are well known, no structural concept based on these techniques has been reported.

Pultruded Beams Assembled by means of Fasteners

The pultruded beam assembly can be carried out following a number of procedures. The first concept analyzed here, is based on the traditional way of fastening steel profiles when welding was not reliable.

Numerous fasteners are the core of this type of assembly (Figure 3).

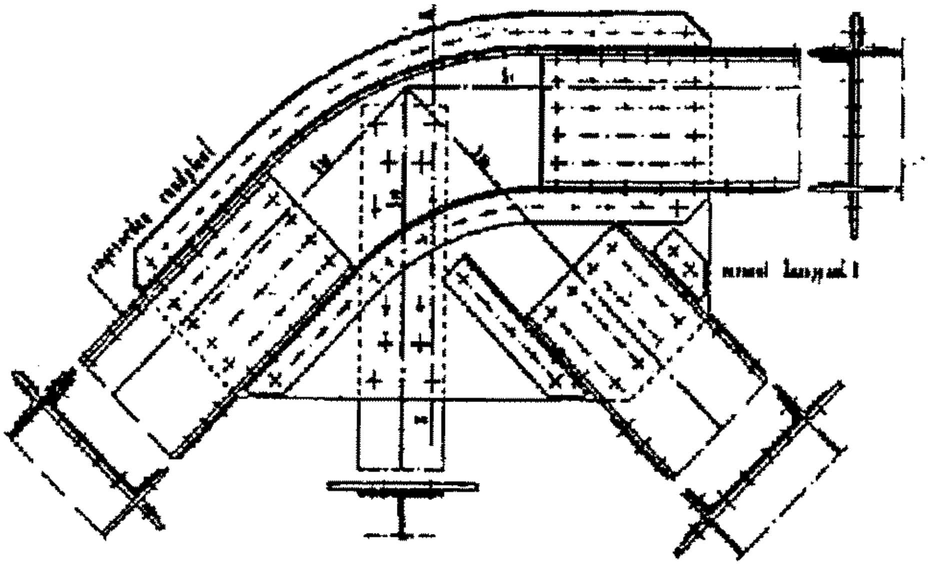

Figure 3.- Detailed sketch of structural detail for composite construction containing numerous fasteners.

Since many applications require the use of non-metallic structures – due to corrosion or chemical attacks – composite fasteners have been developed (Figure 4).

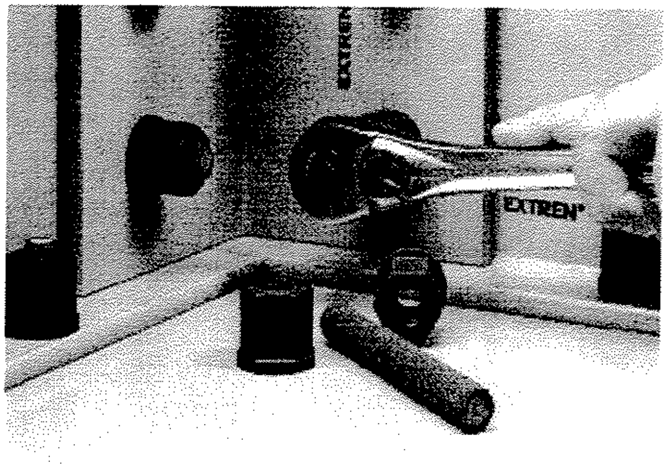

Figure 4. - Composite fasteners for full composite structural applications.

A number of structures have been built following this structural concept. An example of a full composite structure manufactured by means of this technology is shown in Figure 5. Usually, these constructions have been applied to buildings with communication devices due to the electromagnetic wave transmission problem.

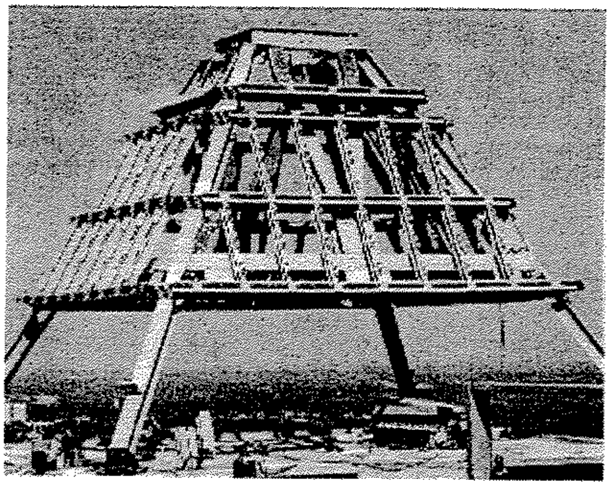

Figure 5. - Full composite structure manufactured by pultruded beams assembled by means of numerous fasteners.

Though, the structural integrity can be demonstrated by using high safety margin, bolted joints in pultruded beams generate stress concentration phenomena.

Pultruded Beams Assembled by the "Snap" joint concept

The traditional "snap" concept has been applied to full composite thee-dimensional structures. This structural concept is very well known and is represented in Figure 6.

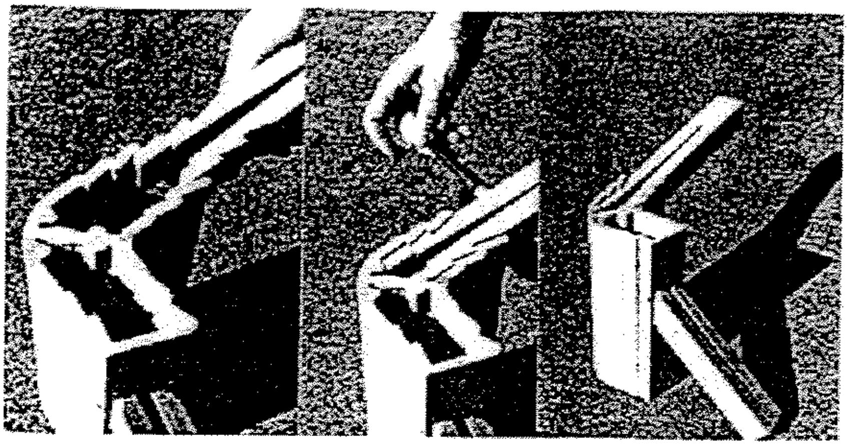

Figure 6. - "Snap" joint concept.

The electrical transmission tower represented in the Figure 7 is an example of application of the "snap" joint concept.

Pultruded Beams Assembled by means the Grid Concept

Pultruded composite grids are widely used in offshore structures. This concept is based on three transverse profiles, which are joined to the longitudinal beams by means of bonded connections.

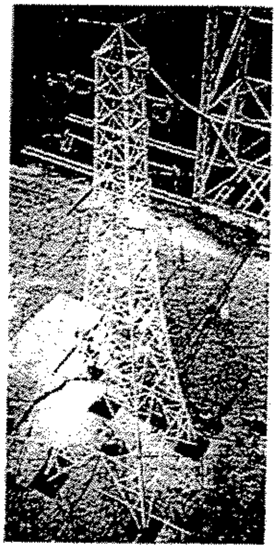

Figure 7. - Electrical tower manufactured by means of the "snap" joint concept.

The top and bottom transverse pultruded profiles present rectangular cavities.

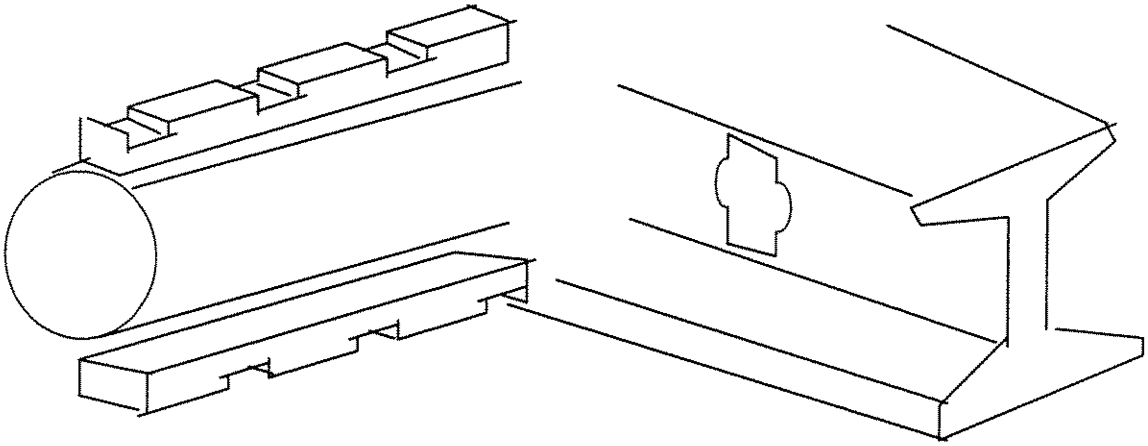

Figure 8. - Scheme of the pultruded grid joint

A pultruded composite grid for offshore applications is shown in Figure 9.

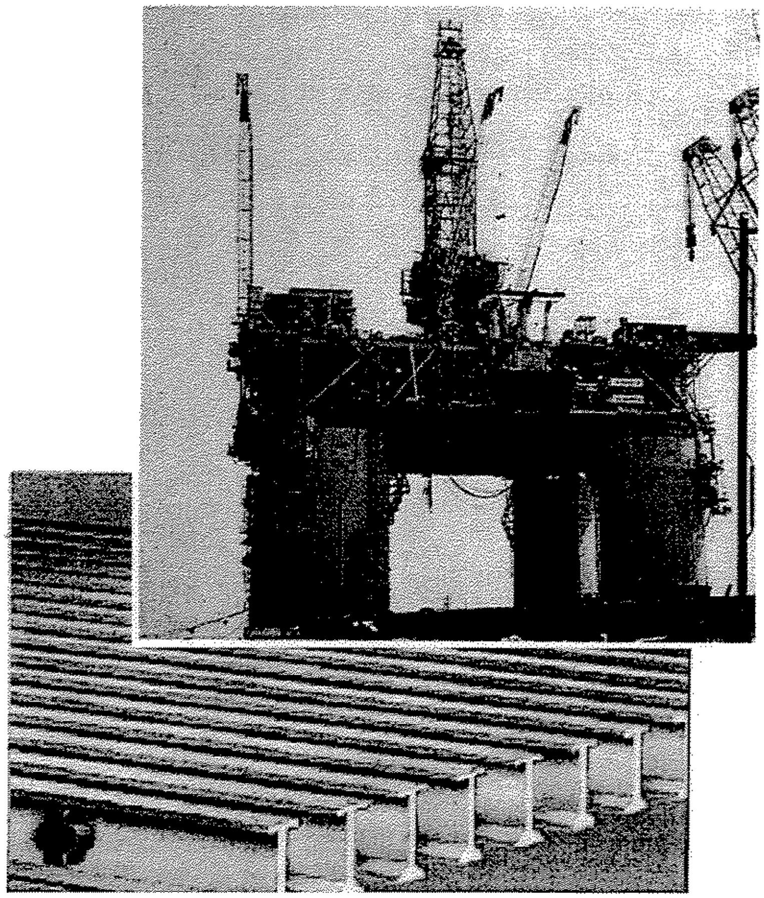

Figure 9. - Pultruded composite grid for offshore applications.

This scheme is clearly more efficient that crossing directly pultruded transverse beams across longitudinal profiles because of the rectangular cavities and the bonded joint.

The ACCS (Advanced Composite Construction System) Concept

The structural concept known as ACCS is characterized by using modular pultruded profiles with cavities. "Dog bone" cross-section pultruded beams are used to assembly 2- and 3-D composite structures. This concept is shown in Figure 10.

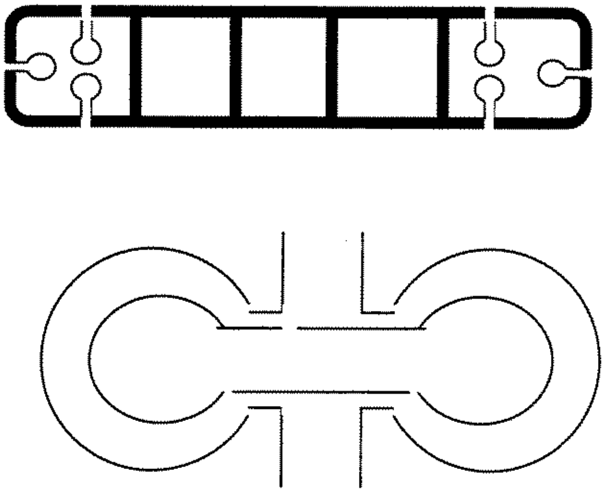

Figure 10. - Scheme of the ACCS system.

A number of applications have been carried out by means of this technology:

- Office Buildings
- Bridge decks
- Bridge Pilars
- Bridge Maintenance Hallways
- Traffic signals

One of the most famous applications is the Tay River Bridge (Scotland) represented in the Figure 11.

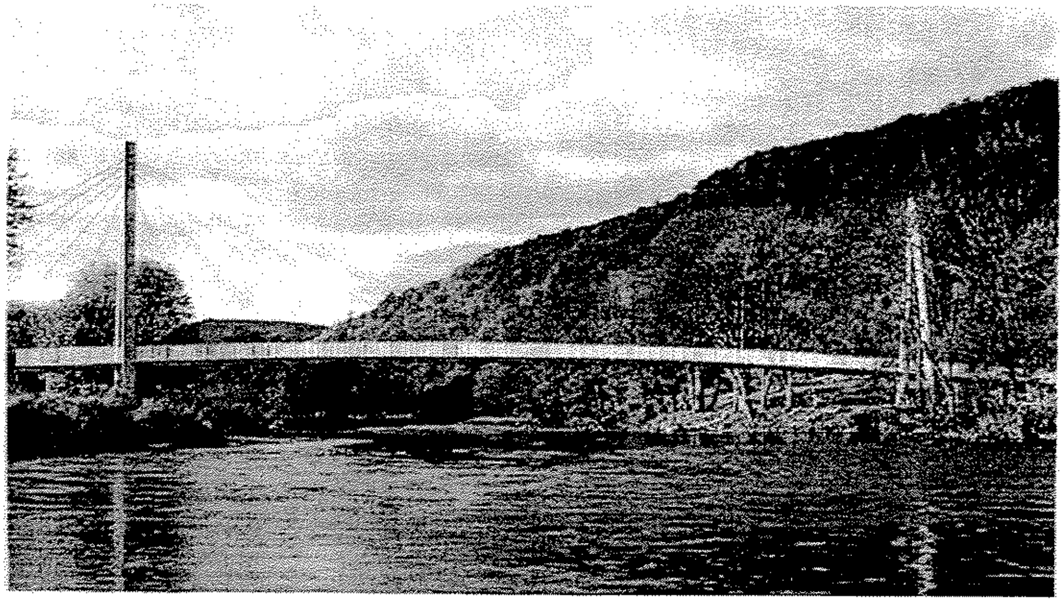

Figure 11. - Tay River Bridge (Scotland).

Conclusions

The structural concepts here analyzed are valid for low-medium loaded applications but no structural scheme for high loads has been found.

An innovative solution will be described in the following section of this paper. It seems clear that pultrusion is a very promising manufacturing process for beams and profiles but it presents mechanical problems for joint solutions.

Nowadays there is a number of manufacturing techniques which are being successful in the design of 3D complex pieces and therefore for joint parts.

PRELIMINARY INNOVATIVE CONCEPTS

Review of the manufacturing processes

The manufacturing process is a key issue in the design of a new Structural Concept for the Topside Area. Designing with steel does not present any problem in terms of manufacturing processes since cutting and welding carbon steel profiles is simple, efficient and cheap.

The manufacturing process in our case must be selected in terms of:

- Feasibility
- Cost

According to the list shown above, the following manufacturing processes will be analyzed:

- Pultrusion
- Filament Winding
- Resin transfer Processes
- Others

Pultrusion

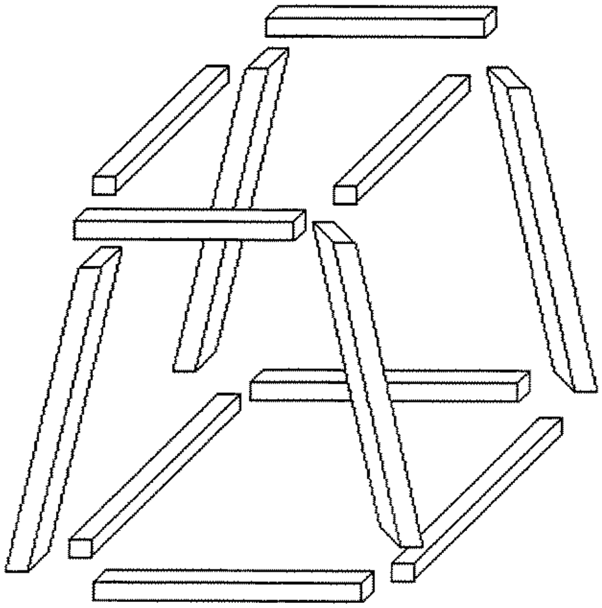

Figure 12. - Scheme of a Structural Concept manufactured by pultrusion.

The advantages of this design are:

- High Stiffness and Strength
- Low-cost Process
- Reliable Manufacturing Technique

A major disadvantage is the definition of the joints. Recently several structures have been presented for construction designed by using pultruded profiles. The joints are solved by means of nodes.

In our case, high loads exist in the intersection between the chords and the transverse profiles. A very stiff and strong joint is required in order to meet the stiffness and strength requirements. Pultruded profiles might be used in addition to other pieces made by means of other manufacturing processes.

Figure 12 shows a preliminary design of a modular structure consisting of a pultruded structure.

Filament Winding

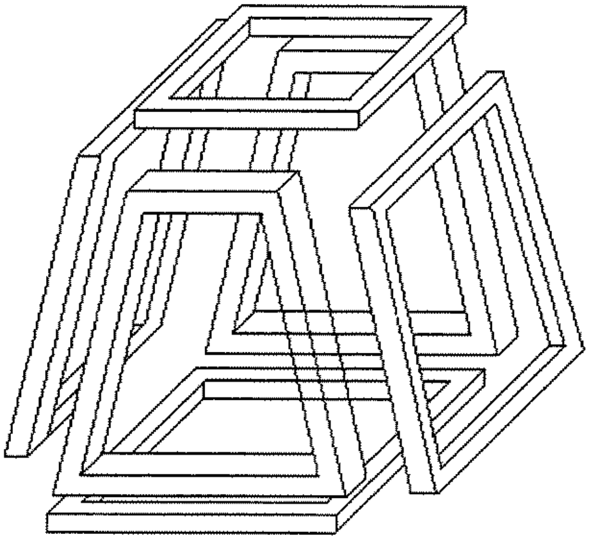

Figure 13. - Scheme of a structural concept manufactured by frames made of filament winding.

A preliminary design of a modular composite structure based on wounded composite frames is represented in Figure 13. This technique is being used in Europe for high structural applications. The manufacturing process is filament winding.

The major advantages of this design are

- High Stiffness and Strength of the beams of the frame (mechanical properties similar to the pultruded beams)

- High Stiffness and Strength of the joints due to the fact that fibers are continuous along the perimeter of the frame.

A mayor disadvantage is the complexity of the process, since this composite frame cannot be manufactured by using a standard filament-winding machine. Several improvements must be in a standard filament-winding machine made in order to appropriately process this type of configuration.

Resin Transfer Processes

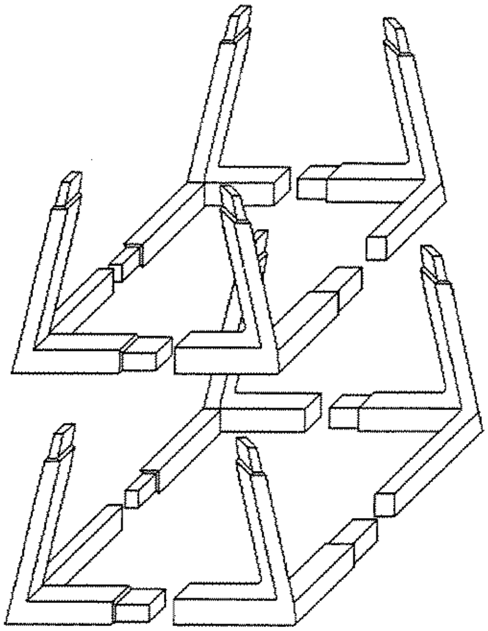

Figure 14. - Scheme of a structure made out of resin transfer molded pieces.

A preliminary design of a modular structure based on moduli manufactured by Resin Transfer Molding (R.T.M.) is represented in Figure 14.

The major advantages of this design are:

- High Stiffness and Strength of the beams of the frame (mechanical properties similar to the pultruded beams)
- High Stiffness and Strength of the joints due to the fact that the whole modulus, including beams and joints, is manufactured in just one shot (R.T.M. process).
- R.T.M. process has been used for the last decades worldwide, the results for structural applications being nowadays outstanding from both points of view: cost and mechanical properties.

Description of an innovative concept

A new manufacturing process for an innovative structural concept consists of combining the resin transfer technology and pultrusion:

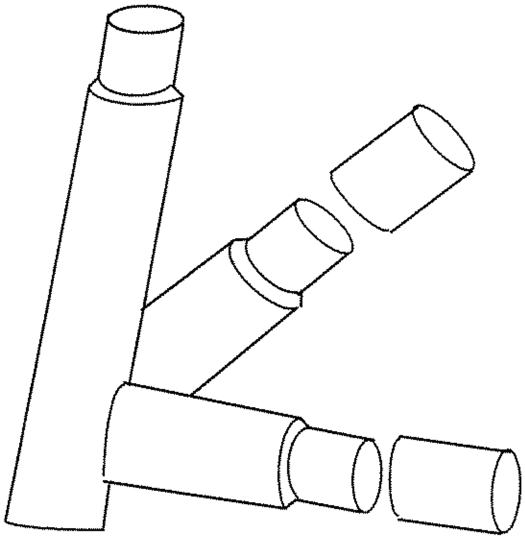

Figure 15. - Detail of a modulus made by means of a combined manufacturing process: resin transfer molding and pultrusion.

The scheme shown in Figure 16 represents a modulus made by means of resin transfer molding and two pultruded profiles.

A whole composite structure could be made by using one mold, since this piece can be assembled to another two or three to make a 3 or 4 chord general structure

Also, by means of this procedure, it is possible to make a composite structure whose width and height vary along the longitudinal axis.

The variable width and height are obtained by using pultruded profiles whose length is variable: To assembly the structure section at the bottom, long pultruded profiles will be used and shorter profiles will be included for upper sections. The connections between the resin transfer pieces will be carried out by means of bonded joints. The bonded surface will be sized in order to meet the stiffness and strength requirements. The joints between the resin transfer molding and the pultruded beams will also be made by means of bonded joints.

The critical areas are the intersections between the chords and the transverse beams. These sections will be made entirely by means of resin transfer molding. The thickness and the orientation of the fibers will be optimized, such that the static and fatigue strengths will be appropriate for the current design. The joints between the RTM piece and the pultruded beams are carried out in areas where the stress gradients are low.

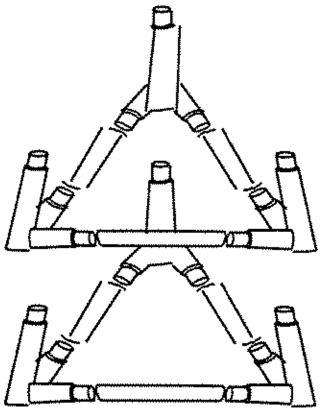

Figure 16. - Scheme of the assembly of the structure.

Not only pyramidal structures can be performed, also prismatic structures can be designed following the same structural concept (Figure 17):

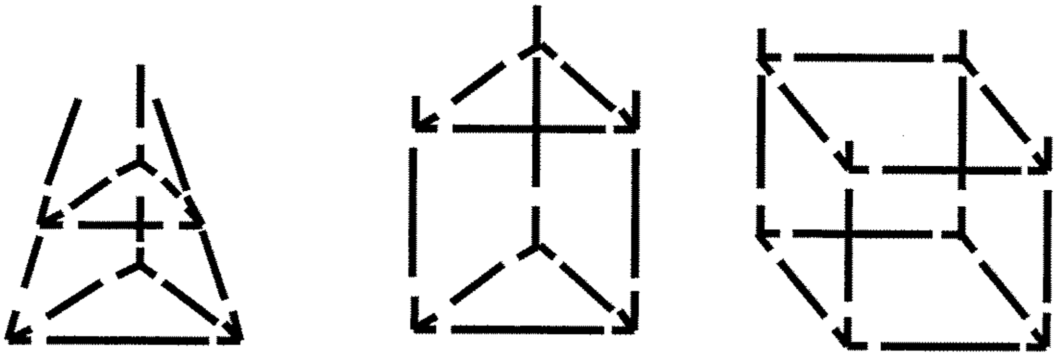

Figure 17. - Pyramidal and prismatic structures made out by the current concept.

For a number of topside structures, rectangular section truss structures is required. Generally speaking, there is no restriction in terms of section geometry. However, a polygonal scheme is recommended in order to use just one mold and reduce the tooling cost of the project. This aspect results critical in terms of cost efficiency since resin transfer molding tooling usually represents an important fraction of the budget for low series applications.

The use of textile composites as preforms for connections

The present concept is based on two construction systems:

- Pultruded profiles
- R.T.M. pieces

The analysis of a truss structure manufactured by means of this technology will show that pultruded profiles are loaded by tension and compression forces and bending moments. Pultruded profiles will bear very high loads as long as the design of the cross section, laminate thickness and layout is properly done.

The critical area will be located in the R.T.M. piece, which is represented in Figure 15. lso, another key aspect in terms of behavior is the preform. Since the stress concentration areas are located in this part, a very efficient preform is recommended.

CASE STUDY OF A COMPOSITE FLARE BOOM STRUCTURE

The present study consists of two parts:

- Part I. First a steel flare boom is analyzed. The deflection, safety margin and the
- Part II. The design of the joint between the chord and the transverse beams will be studied by means of the finite element method. Resin transfer molding and braiding technologies will be used for the conception of the joint. The results from both manufacturing technologies will be discussed.

Reference Case: Steel Flare Boom

Initially, an analysis of a steel flare boom structure (Figure 18) has been carried out in order to evaluate the reference deflection and lowest natural frequency. The mesh is composed of 774 quadratic beam finite elements and 1493 nodes.

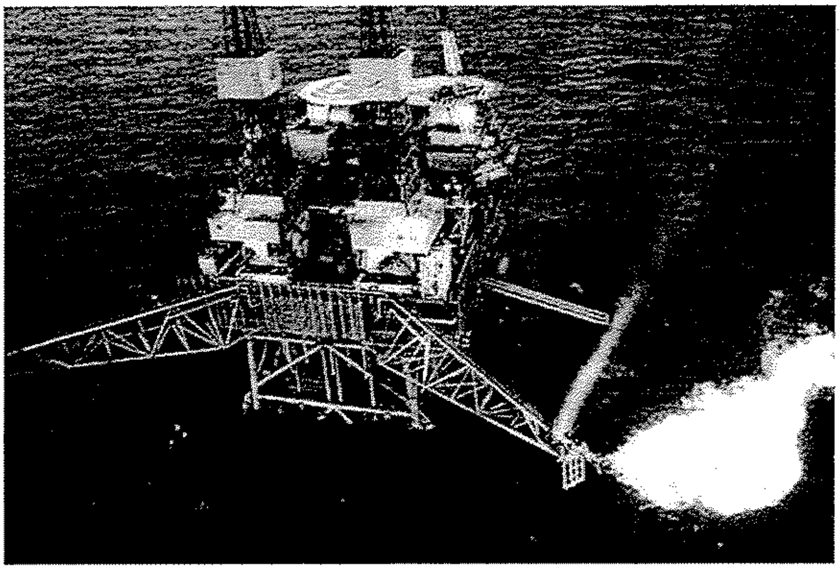

Figure 18. - Offshore structure showing the flare boom (right).

The loads applied are the following:

- Tip load: 12 000 lb.
- Wind loads: 0.2175 lb. / in
- Weight of the structure: 54400 lb.

The lowest nodes have been pinned accordingly to the actual boundary conditions of the boom.

The cross-sections of the beams correspond to the following profiles, from top to bottom:

- Type I: diameter 6 5/8” thickness: 0.28”
- Type II: diameter 8 5/8” thickness: 0.322”
- Type III: diameter 10 ¾” thickness: 0.365”
- Type IV: diameter 12 ¾” thickness: 0.375-0.5”
- Type V: diameter 14” thickness: 0.5-0.625”
- Type VI: diameter 20” thickness: 0.5-1”
- Type VII: diameter 24” thickness: 0.5-1.25”

The results obtained are the following:

Deflection: 3.82 inches
Lowest Natural Frequency: 1.28 Hz
Second Natural Frequency: 2.12 Hz
Third Natural Frequency: 4.62 Hz

The lowest natural frequency 1.28 Hz and the second 2.12 Hz, associated to a bending mode. The third (4.62 Hz) corresponds to a torsion mode.

The weight reported is 54400 lb.

DESIGN OF A FLARE BOOM STRUCTURE

The design of the composite flare boom is different to the steel one (Figure 19).

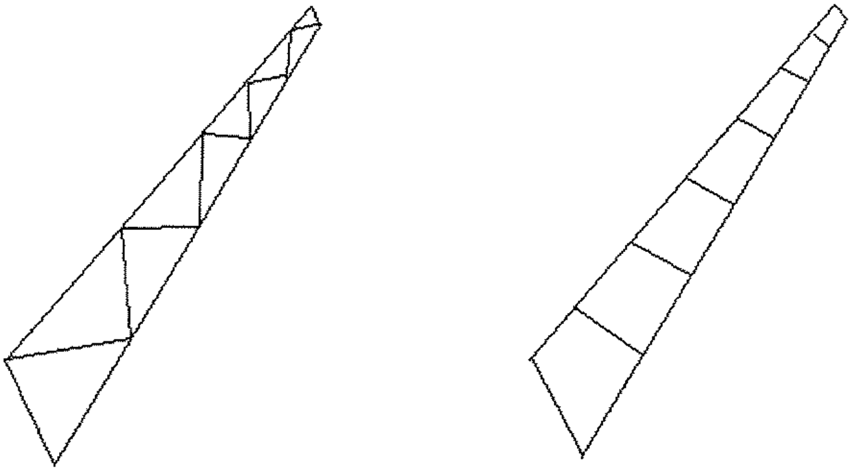

Figure 19. - Steel (left) and composite (right) flare boom designs.

First, a sensitivity study was carried out in order to determine the values of the chord diameter and the brace diameter. According to the results, the following values were used in the analysis:

Chord diameter: 28"
Brace diameter: 22"

A maximum weight saving of six is reported for the diameters shown above.
The cross-sections of the beams correspond to the following ranges, from top to bottom:

- Type I: diameter 14" thickness: 0.5"
- Type II: diameter 20" thickness: 1"

In order to assess the efficiency of this structure against the steel structure, a hybrid system has been used. The lay-out of the beams correspond to the following ranges, from top to bottom:

• Type A:	100% glass fiber
• Type B:	1/3 carbon fiber and 2/3 glass fiber
• Type C:	2/3 carbon fiber and 1/3 glass fiber
• Type D:	100% carbon fiber

Balanced fabrics for both carbon and glass fibers have been used. The manufacturing process selected has been resin transfer molding.

The properties for the carbon fiber fabric / epoxy matrix composite ply are:

$E_1 = E_2 =$ 9.33×10^6 psi

$\nu =$ 0.12

$G_{12} =$ 5.8×10^5 psi

$\varepsilon_{1max} = \varepsilon_{2max} =$ 0.01

$\gamma_{max} =$ 0.05

And the properties for the glass fiber fabric are:

$E_1 = E_2 =$ 8.5×10^5 psi

$\nu =$ 0.15

$G_{12} =$ 5.2×10^4 psi

$\varepsilon_{1max} = \varepsilon_{2max} =$

$\gamma_{max} =$ 0.06

The results obtained are the following:

Deflection: 11.38 inches

Lowest Natural Frequency: 1.12 Hz

Second Natural Frequency: 1.14 Hz

Third Natural Frequency: 2.10 Hz

The weight reported is 17657 lb.

Comparative Results

The comparative results are given in Table 2:

Table 2. - Comparative Results of a Steel and a Composite Flare Boom

	Steel Flare Boom	Composite Flare Boom
Deflection (in)	4.043	5.054
1st Frequency (Hz) Bending mode	1.28	1.12
2nd Frequency (Hz) Bending mode	2.12	1.14
3rd Frequency (Hz) Torsion mode	4.62	2.10
Weight (lb.)	106212	17657 (6 times less)

DESIGN OF A CHORD-TRANSVERSE BRACE JOINT

The design of the joint between the chords and the transverse beams is a key issue from the feasibility point of view. Two manufacturing processes have been studied:

- Resin Transfer Molding
- Braiding

Sensitivity study of the Joint Manufactured by R.T.M

A sensitivity study has been carried out in order to assess the influence of the orientation of the fabrics to be used in the resin transfer molding. Two plies consisting of balanced fabrics initially oriented at [0/90] and [+45/-45] have been used. The following parameters have been studied:

- Fraction of fabrics at [0/90] and [+45/-45]
- Orientation of fabric [0/90]

The material used presents the following properties:

$E_1 = E_2 =$	9.33×10^6 psi	$\varepsilon_{1max} = \varepsilon_{2max} =$	0.01
$\nu =$	0.12	$\gamma_{max} =$	0.05
G12=	5.8×10^5 psi		

The maximum strain criterion is obtained in Figure 20. The value of the minimum strain is 0.025, corresponding to a [+45/-45] fabric.

Sensitivity study of the Joint Manufactured by Braiding

Two plies consisting of balanced fabrics have been used. The following parameters have been studied:

- Proportion of fibers at [0] and [+θ /-θ]
- Orientation of fabric [+θ /-θ]

A macro mechanical model has been used to evaluate the properties:

$E_f =$	3.63×10^7 psi	$G_f =$	1.39×10^7 psi
$E_m =$	5.34×10^5 psi	$G_m =$	1.98×10^5 psi
$\nu_f =$	0.3	$\varepsilon_{f\,max} =$	0.01
$\nu_m =$	0.35	$\varepsilon_{m\,max} =$	0.045

The maximum strain criteria are shown in Figure 21. The value of the minimum strain is 0.03, corresponding to a $[0_{30}/+30/-30_{50}]$ fabric.

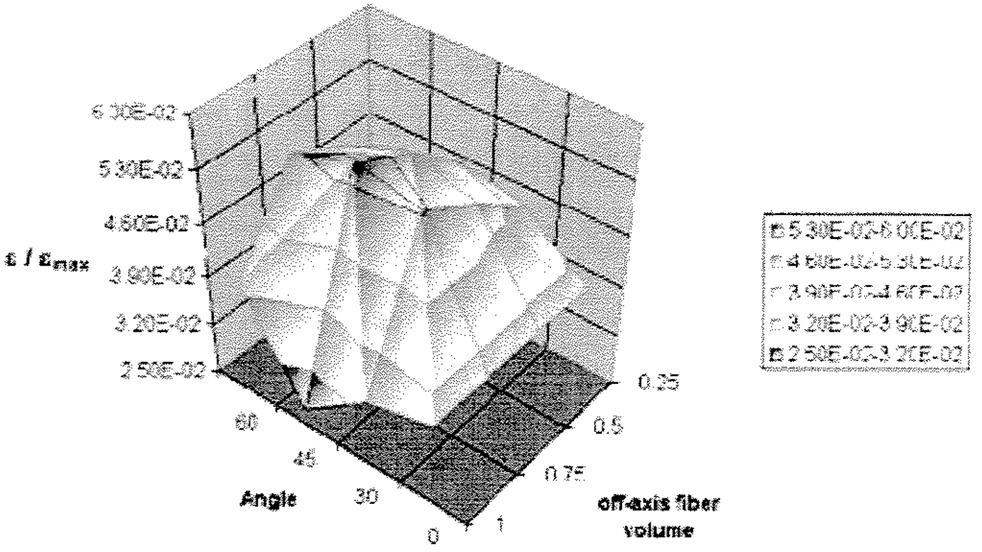

Figure 20.- Maximum strain criteria for R.T.M. configuration.

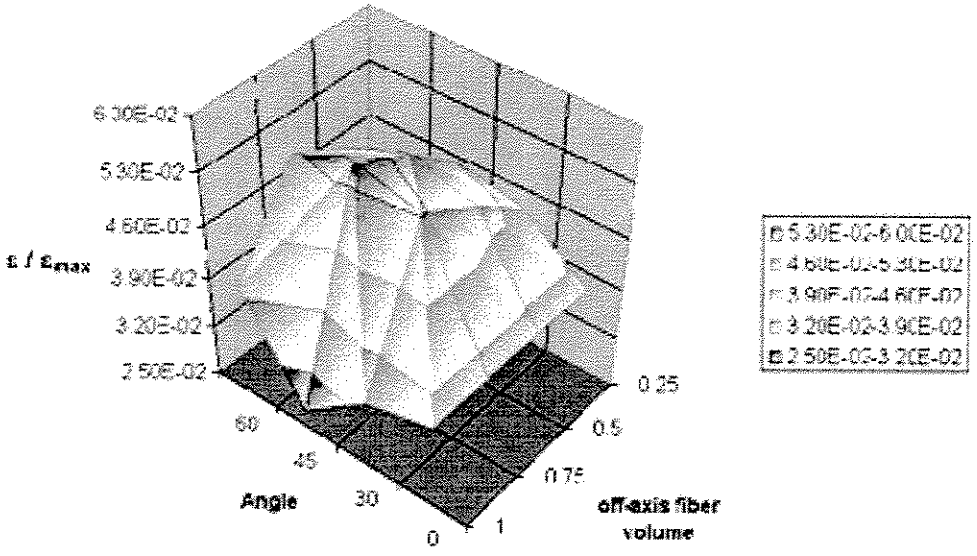

Figure 21.- Maximum strain criteria for braiding configuration.

COMPARISON BETWEEN STEEL AND COMPOSITE FLARE BOOM STRUCTURES

The conclusions of the work done up to now can be drawn from the following example: a flare boom for a typical offshore platform from the Gulf of Mexico with this new design.

Weight Analysis

STEEL FLARE BOOM:

Boom length: 170 ft	
Weight	
• Chords (3) :	39,711 lb.
• Transverse braces:	23,592 lb.
• Diagonal braces:	42,909 lb.
• **Total boom weight:**	**106,212 lb.**
• Platform weight:	10,000 lb.
• Flare tip:	2,000 lb.
• Others:	3,000 lb.
Deflection:	4.04 in
Safety margin:	3

COMPOSITE FLARE BOOM:

Boom length: 170 ft	
Weight	
• Chords (3) :	11,075 lb.
• Transverse braces:	6,582 lb.
• Diagonal braces:	0 lb.
• **Total boom weight:**	**17,657 lb.**
• Platform weight:	10,000 lb.
• Flare tip:	2,000 lb.
• Others:	3,000 lb.
Deflection:	5.05 in
Safety margin:	5

Cost Analysis

STEEL FLARE BOOM:

Raw Materials	
\$2.5/lb X 106,212 lb. =	\$265,530
Coating	
\$0.8 X 106,212 lb. =	\$ 84,970
Total cost	**\$350,500**

COMPOSITE FLARE BOOM:

Raw Materials	
Pultruded transverse braces	
\$10/lb X 6,582 lb. =	\$65,820
Chords	
Pultrusion (hybrid 1/3 carbon)	
\$15/lb X 7,383 lb. =	\$110,750
RTM (hybrid 1/3 carbon)	
\$22/lb X 3,691 lb. =	\$81,202
RTM Mould	
\$100,000/5 =	\$20,000
Adhesives	
\$30/lb X 200 lb. =	\$6,000
Foam	
\$25/lb X 50 lb. =	\$1,250
Estimated Assembly Costs	
\$1.5/lb X 17,657 lb. =	\$26,486
Coating	
\$10/ft^2 X 2,563 ft^2 =	\$25,630
Total cost	**\$337,138**

CONCLUSIONS

A comparative study of steel and composite flare booms subjected to mechanical loads (tip load, own weight and wind loads) has been carried out. The conclusion of this analysis is that the composite flare boom structure composed of three chords and transverse beams forming frames perpendicular to the flare longitudinal axis is the an efficient solution.

The composite solution exhibits about the same stiffness and lowest natural frequency as the steel structure. The safety margin is higher due to the outstanding specific strength of organic matrix composite materials compared to steel.

The design of the chord has also been studied. Two manufacturing processes have been analyzed: resin transfer molding and braiding. Two sensitivity studied have been carried out:

- For the resin transfer molding joint, the stress and strain components and the maximum strain criteria have been obtained as a function of the fraction of fabrics at [0/90] and [+45/-45] and the orientation of fabric [0/90]. The value of the minimum strain reported has been 0.025, corresponding to a [+45/-45] fabric.

- For the braiding process, the stress and strain components and the maximum strain criteria have been obtained as a function of the fraction of fibers at [0] and [+θ /-θ] and the orientation of fabric [+θ /-θ]. The value of the minimum strain reported has been 0.03, corresponding to a $[0_{30}/+30/-30_{50}]$ fabric.

Therefore, the conclusion of this study is that resin transfer molding seems to be more competitive for the joint chord-transverse beams than braiding in terms of maximum strain.

The weight of the composite design is six times less than the steel structure. The cost analysis is lightly favorable for the composite flare boom.