# MALECON: A NEW FIBER-METAL HYBRID LAMINATED MATERIAL FOR OFFSHORE RENEWABLE ENERGY

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**Keywords:** Composite Material, Fiber-Metal Hybrid Material, Offshore Wind Turbines.

## Abstract

*Composite materials are widely becoming the choices for many structural applications especially in offshore industry fields, driven by lightweight and corrosion resistance compared to traditional metal. Until recently, interest has focused on the use of them in support structures of offshore wind turbines (OWT). The prospect of deep water exploration and multi-MW turbine's application is generating a new impetus for high performance material, which aims at increasing load bearing capability and if possible saving weight and cost simultaneously. Performance of a new fiber-metal hybrid material developed specifically for the marine industry is presented in this paper. Simulation models of benchmark examples with the new hybrid material were analyzed in different load cases. Several improved parameters are put forward in order to explicit the performance of this new material to be used in towers of OWT clearly. Results show that within certain limits and with optimal configurations, the new hybrid material is efficient both from the points of mechanical performance and cost competitiveness compared to his counterpart metal.*

## 1 Introduction

Offshore wind generation is expected to increase significantly with the urgent demand for sustainable resources in the world. A considerable number of OWTs have been installed in Europe, especially in countries like Denmark, Sweden, England and Germany etc. (Ref 1,2). Interest in offshore wind energy is growing in other countries also and considerable projects are reaching design stage in the near future (Ref 3,4). Generally speaking, the construction cost of offshore wind farm is an obvious factor that contributes negatively to the efficiency of the wind energy compared to on land exploration (Ref 5). Larger wind turbines in higher air positions and deeper water locations are a solution to reduce the cost for accessing to greater wind speeds. However, further requirements for reliable and economic towers would be one of major challenges corresponding to the rapid development of OWTs (Ref 6). The tallest tower currently serviced in Beatrice demonstration OWT farm is typically tubular steels (Ref 7). It consists of five sections, tapering from 6 meters at the height of the foundations to 5.5 meters at the top. The completed height of the tower is 114 meters. The tower weights around 750 tons considering the quantities of connection pieces. Larger diameters would be required for towers of next generation wind turbines for the structural design of tubular steel tower is dominated by ultimate and fatigue limit state, especially the shell buckling leads to high dimensions for the steel sections (Ref 8). The choice of combination of material for tower sections can take advantages of both corrosion resistant and easy fabricated properties of composites (Ref 9). It might meet the demanding of the new generation wind turbines with high performance, that is to increase the bearing capability and if possible saving weights and cost simultaneously. The advantages of a new concept of sandwich tower sections and corresponding joint techniques have been presented by P.Schaumann in his research, where the properties and configurations of core material result in different load capacities, (Ref 10,11). In this paper, the detailed performances of a new fiber-metal hybrid material specifically for the marine industry are discussed, concerning the basic bearing capability and buckling resistance of the material particularly required by towers of OWT

## 2 Fiber-Metal Hybrid Material-MALECON

The material-MALECON studied here is a new fiber-metal hybrid material developed specifically for marine industry use. It stands for ‘Material Laminado Estructural para Construcción Naval’, and it is a patented hybrid material of ETS Ingenieros Navales of Universidad Politécnica de Madrid (Ref 12). The basic concept of the material is configurations of layers of metal sheet alternating with plies of composite material which is connected with outer metal layers by structural adhesives, as shown in Fig.1.The reinforcement of the material would be typical E-GLASS fibers with Vinyl Ester matrix and the metal sheet would be steel.

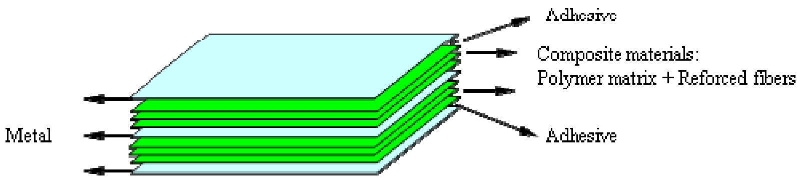


**Figure 1.** Concept of Fiber-Metal Hybrid material

Similar to most composites currently used, MALECON is meeting an increasing demand for construction materials that are strong, lightweight, durable and easy to assemble. Moreover, it can be designed to be isotropic or anisotropic; Fatigue behavior can be improved due to the multilayer concept; Corrosion is kept confined in the outermost metal sheet, and more efficiently controlled; Fire safety is improved because polymer is encapsulated between metal sheets; Manufacture is improved compared with the traditional composite materials, because metal sheets can be used as tooling during the resin infusion and curing processes; Joining techniques are conveniently improved by combining adhesive joints for inside layers with welds for the outer sheets. Even though the purchase cost of composite components sometimes exceeds that of their metallic counterparts, the whole-of-life cost is often lower than that of conventional steel and even greater when replacing expensive corrosion-resistant materials in marine industry use, for they are often directly competitive on initial installation and less expensive to maintain. As well as expected benefits, a number of mechanical and economic parameters are introduced to identify the efficiency of the new material for structural use by numerical simulations.

## 3 Numerical Simulations

In order to investigate the performance of MALECON to be used in the towers of OWT, several configurations and three kinds of typical load cases, concerning the basic load bearing capability and buckling resistance particularly, are assumed here. Configurations optimum economic performance and load capabilities of the material are presented by following parameters study

### *3.1 Configurations of Fiber-Metal Hybrid Material*

They are four types of cross section of the fiber-metal hybrid material being assumed here, named MALECON_1A, MALECON_1B, MALECON_1C and MALECON_1D respectively.

The main differences among them are locations and quantities of steel layers and composite packages which are fabricated with specially designated polymer matrix and reinforced fibers as talked above. The configurations of them are shown as figure. 2.

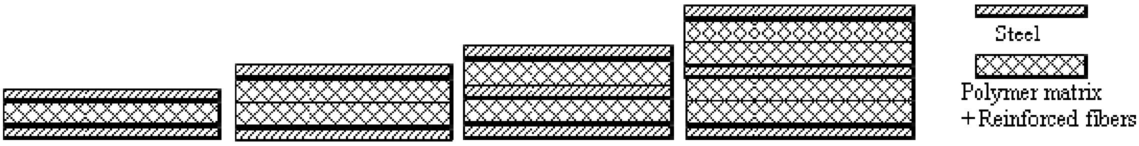


**Figure 2.** Configurations of Fiber-Metal Hybrid material sections

Optimal configurations of the new fiber-metal hybrid material-MALECON are discussed by cases study as follow

*3.2 Benchmark Example*

Take a simply supported panel as an example, composite sections of MALECON_1A, MALECON_1B, MALECON_1C and MALECON_1D are introduced respectively in the models to get the mechanical and economical features of the new fiber-metal hybrid material. Loading cases can be divided into three categories, such as:

①Load case 1(Flexure): uniform pressure P=10kPa.
②Load case 2(Buckling Load): edge compression load Nx
③Load case 3(Elastic Tensile Strength): edge tensile load Tx

*3.3 Analysis methods*

Numerical simulation of the fiber-metal hybrid material is carried on by ESAComp, which is the software of Componeering Inc. for the analysis and design of composite laminated structural element. The metal plies and other plies of composite package of polymer matrix with reinforced fibers are specified in the active case of ESAComp by typing in corresponding physical data necessary for analysis. They are illustrated in table 1

| Ply Specification | Details |
|---|---|
| STEEL<br>0 º | Physical nature: Homogeneous ply. Mechanical behavior: isotropic. Density:7800Kg/m$^3$<br>Moduli:E_1=200Gpa,G_12=76.9230769Gpa. Poisson's rations:Nu_12=0.3<br>First failure stresses and strains:<br>Direction1 Stress X-t 510Mpa ,Direction1 Stress X-c 510Mpa<br>Direction1 Strain X-eps,t 0.255%, Direction1 Strain X-eps,c 0.255% |
| ADHESIVE<br>0 º | Physical nature: Adhesive ply. Mechanical behavior: isotropic. Thickness:1mm.<br>Density:1500g/ m$^2$.Moduli:E_1=2.1374Gpa,G_12=0.79163Gpa.<br>Poisson's rations:Nu_12=0.35<br>First failure stresses and strains:<br>Direction1 Stress X-t 11Mpa,Direction1 Stress X-c 11Mpa<br>Direction1 Strain X-eps,t 0.5146%Direction1 Strain X-eps,c 0.5146% |
| MAT-E-600B<br>VINILESTER<br>0 º | Physical nature: Reinforced ply. Mechanical behavior: isotropic. Density:1193/m$^2$.<br>Thickness: 0.61mm. Fiber volume fraction:37.72%.<br>Form of reinforcement: Mat,discontinous fibers<br>Moduli:E-1=14.236Gpa,G-12=5.357Gpa. Poisson's rations:Nu-12=0.3287<br>First failure stresses and strains:<br>Direction1 Stress X-t 160Mpa, Direction1 Stress X-c 150Mpa<br>Direction1 Strain X-eps,t 1.1239%, Direction1 Strain X-eps,c 1.0537% |
| TEJ-E-500C<br>VINILESTER | Physical nature: Reinforced ply,other. Mechanical behavior: Transversely isotropic 23<br>Density: 1855.29g/m$^2$. Thickness:0.4mm.<br>Fiber volume fraction:48.51%,Directionalityf_1&2:50%<br>Form of reinforcement: weave,plain<br>Moduli:E_1=9.32Gpa,E_2=36.96Gpa,G_12=3.347Gpa,G_23=17.0716Gpa |

| | |
|---|---|
| | Poisson's rations:Nu_12=0.0825,Nu_23=0.0825<br>First failure stresses and strains:<br>Direction1 Stress X-t 350Mpa, Direction1 Stress X-c 350Mpa<br>Direction1 Strain X-eps,t 3.755%, Direction1 Strain X-eps,c 3.755%<br>Direction2 Stress X-t 320Mpa, Direction2 Stress X-c 320Mpa<br>Direction2 Strain X-eps,t 0.8658%, Direction2 Strain X-eps,c 0.8658% |
| 2.5mm CORE | Physical nature: Adhesive ply. Mechanical behavior: isotropic<br>Thickness: 2.5mm. Density:188g/m$^2$.Moduli:E_1=3.51633Gpa,G_12=1.30234444GPa<br>Poisson's rations:Nu_12=0.35<br>First failure stresses and strains<br>Direction1 Stress X-t 82.74Mpa, Direction1 Stress X-c 82.74Mpa<br>Direction1 Strain X-eps,t 2.353%,Direction1 Strain X-eps,c 2.353% |
| UNI-E-1200<br>VINILESTER<br>45$^o$<br>-45$^o$ | Physical nature: Reinforced ply, unidirectional<br>Mechanical behavior: Transversely isotropic 23<br>Thickness:0.44mm,Density:1333.33g/m$^2$.Fiber volume fraction:45%<br>Moduli:E_1=31.161Gpa,E_2=7.452Gpa,G_12=2.738Gpa,G_23=2.781Gpa<br>Poisson's rations:Nu_12=0.3397,Nu_23=0.3397<br>First failure stresses and strains<br>Direction1 Stress X-t 500Mpa,Direction1 Stress X-c 50Mpa<br>Direction1 Strain X-eps,t 1.6046%,Direction1 Strain X-eps,c 0.1605%<br>Direction2 Stress X-t 500Mpa,Direction2 Stress X-c 50Mpa<br>Direction2 Strain X-eps,t 6.7096%,Direction2 Strain X-eps,c 1.82615% |

**Table 1.** Plies properties.

All of these plies are shown in the lay-up list automatically. The new metal-hybrid materials composed by MALECON-1A, MALECON-1B, MALECON-1C, MALECON-1D are made of plies with different orientation and thickness. Load responses of the rectangular panel made of above materials under transverse loads, panel buckling due to in-plane loads and ultimate tensile loads are performed based on ESAComp built-in FE solver. Results are further analyzed with MATLAB software to get the performances that concerned for the structural applications.

## 4 Results and Discussion

### *4.1 Flexural Load Case*

As a kind of long cantilever structure, the towers of OWT are usually suffered from tremendous flexural loads, especially the aerodynamic loads at the top side the tower, which increase greatly with the dimension of the wind turbine and finally results in larger diameter requirement for the bottom of the tower. Since the metal layers are placed at a distance from each other in MALECON_1A, MALECON_1B, MALECON_1C and MALECON_1D, the moment of inertia, thereby the flexural rigidity about the neutral axis of the structure would be increased significantly. Assuming all of them have the same flexural rigidity with mono-steel panel, several parameters are defined here to evaluate the efficiency of the materials resisting to flexural loads. They are FME, RCF, CIF and MVF as follow.

FME is the ratio of the area density of STEEL panel to that of composite panel when assuming the same maximum deflection

$$FME = \frac{\rho_A^S}{\rho_A^{M1i}} \qquad i = A, B, C, D \tag{1}$$

Where, $\rho_A^S$ is the area density of the STEEL; $\rho_A^{M1i}$ is the area density of MALECON-1A, MALECON-1B, MALECON-1C, MALECON-1D respectively

RCF is the ratio of the area price of STEEL panel to that of composite panel when assuming the same maximum deflection.

$$RCF = \frac{C_S^F}{C_{M1i}^F} \qquad i = A, B, C, D \tag{2}$$

Where, $C_S^F$ is the area price of the steel panel in flexure case; $C_{M1i}^F$ is the area price of composite panel in flexure case.

CIF is the correlation index of the area density and price of STEEL panel to that of composite panel when assuming the same maximum deflection.

$$CIF = FME \times RCF \tag{3}$$

MVF is metal volume of composite panel in flexural load case

$$MVF = {STEEL\ THICKNESS} \big/ {PANEL\ THICKNESS} \tag{4}$$

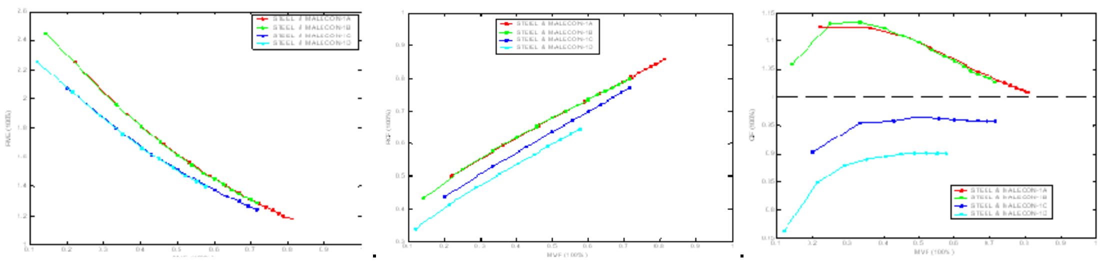

**Figure 3.** FME, RCF and CIF of STEEL and MALECON-1ABCD panels to MVF

From figure 3, we can see, in flexural load case, all values of FME are larger than 1.This implies that the new composite material shows evident property of light weight over steel counterpart. However, the fabrication cost of them is higher as shown in figure 4 by parameter RCF. Taken consideration of both two factors together, MALECON-1A and MALECON-1B are more efficient than mono steel and much better when the metal volume is around 30% in the composites. It is represented by CIF, as shown in same figure 4 illustrates above result by plotting the parameters of the material MALECON-1B FME, RCF, CIF and MVF simultaneously.

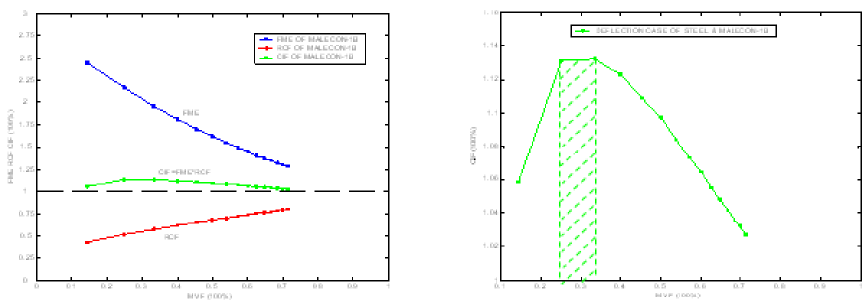

**Figure 4.** Flexural load case results of MALECON-1B (a at left, b at right side)

### *4.2 Buckling Load Case*

Shell buckling is another important factor that leads to high dimension demand for steel sections of OWT towers. In order to evaluate the efficiency of the new materials in buckling load case study, several parameters are defined. They are BME, RCB, CIV and MVB as follow.

BME is the ratio of the area density of STEEL panel to that of composite panel when assuming the same buckling load

$$BME = \frac{\rho_A^S}{\rho_A^{M1i}} \qquad i = A, B, C, D \tag{5}$$

RCB is the ratio of the area price of STEEL panel to that of composite panel when assuming the same buckling load.

$$RCB = \frac{C_S^B}{C_{M1i}^B} \qquad i = A, B, C, D \tag{6}$$

CIB is the correlation index of the area density and price of STEEL panel to that of composite panel when assuming the same buckling load.

$$CIB = BME \times RCB \tag{7}$$

MVB is metal volume of composite panel in flexural load case

$$MVB = STEEL\ THICKNESS \Big/ PANEL\ THICKNESS \tag{8}$$

Where, $\rho_A^S$ , $\rho_A^{M1i}$ , $C_S^B$ and $C_{M1i}^B$ have the same meanings as previously specified in (1) and (2) except for different load case. ‘B’ denotes buckling load case.

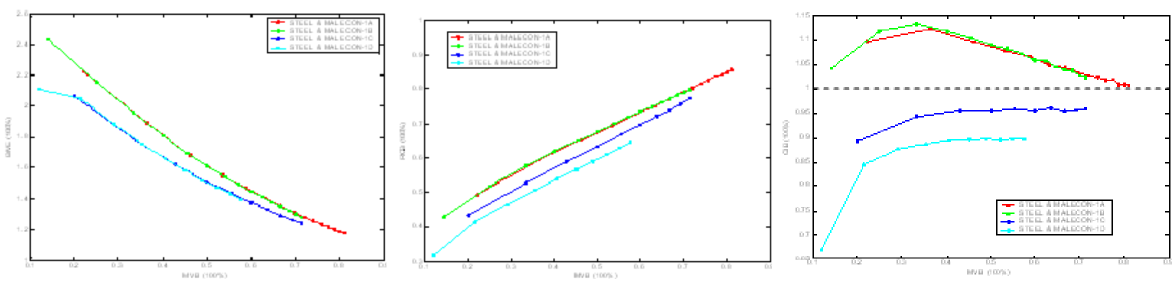

**Figure 5.** BME, RCB and CIB of STEEL and MALECON-1ABCD panels to MVB

From figure 5, we can see, similar to flexural load case, all new hybrid materials are light weight over steel counterpart in buckling load case. However, the fabrication cost of them is still higher as shown in same figure. Taken consideration of both two factors together, MALECON-1A and MALECON-1B are also more efficient than steel structure and the optimum range of MVB of the composites is around 35%.

### *4.3 Tensile Load Case*

The elastic tensile strength of the new material discussed here by specifying same kinds of parameters to evaluate the efficiency of the materials in tensile load case study. They are TME, RCT, CIT and MVT like in paragraphs 4.2 and 4.3 using the same elastic tensile strength.

Here, $\rho_A^S$ , $\rho_A^{M1i}$ $C_S^T$ ,$C_{M1i}^T$ have the same meanings as specified in (1) and (2) also except for different load case. 'T' denotes tensile load case.

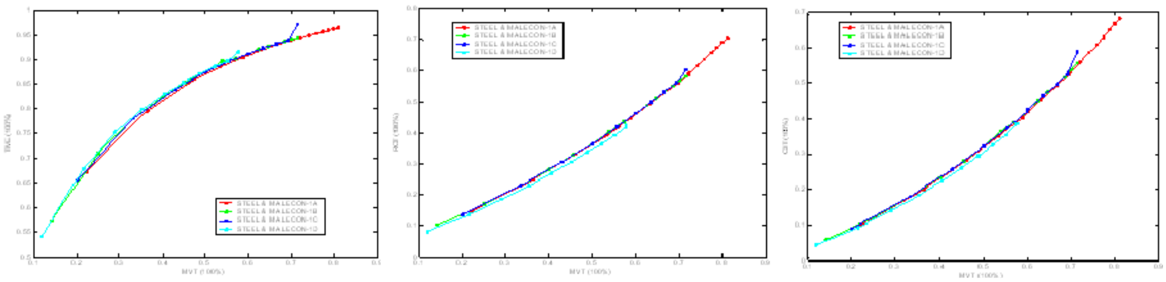

**Figure 6.** TME, RCT and CIT of STEEL and MALECON-1ABCD panels to MVT

From figure 6, we can see, in elastic tensile load case, all new hybrid materials show less efficiency than that steel counterpart, the MALECON panel is heavier than steel panel when meeting the same elastic tensile strength demand. The fabrication cost is higher also as illustrated in the same figure. Taken consideration of both two factors together, MALECON-1A, MALECON-1B, MALECON-1C and MALECON-1D are all obviously less efficient than mono steel. The efficiency of the hybrid materials in tensile load case are depending directly on the metal volume, the larger the better. That proves that the new material is not expected in the uniaxial tensile load conditions.

### *4.4 Sensitivity to Metal Price*

As the metal price shows obviously increasing tendency recently, the sensitivity of the new metal-fiber hybrid material to metal price is also an important economic factor to be learned. Comparing with metal price changing from original supposed value to 1.5 and 2 times, the comprehensive parameters CIF, CIB, CIT of MALECON-1B are illustrated in figure 10 (a – CIF left), (b – CIB center), (c – CIT right).

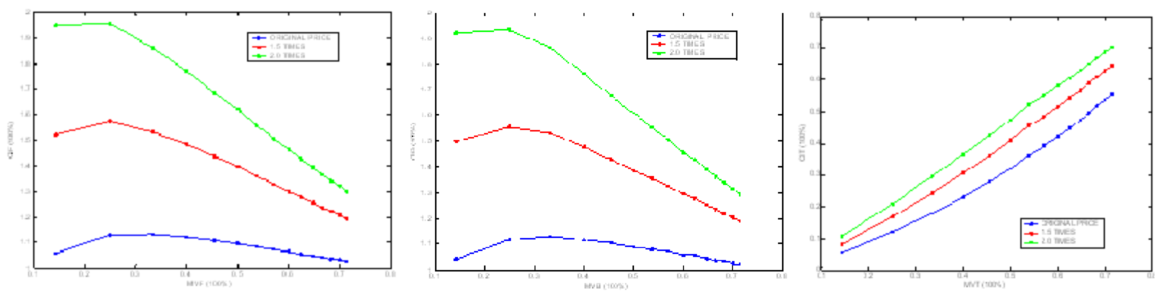

**Figure 7.** Sensitive analysis results of MALECON-1B

From the figure 7, we can see that MALECON-1B shows good economic properties in bending and buckling load cases corresponding to its counterpart mono-steel. With the price of metal increasing, the efficiency of the MALECON is more obvious. As for the tensile load case, the tendency of sensitive property to metal price is the same, while special attention should be paid to the level of tensile force because the coefficient of CIT is still lower than 1.

## 4 Conclusions

In this study, typical mechanical and economic properties of the new metal-fiber hybrid material MALECON, composed of MALECON-1A, MALECON-1B, MALECON-1C and MALECON-1D, are analyzed and compared with those of their counterpart of mono-steel by some improved parameters CIF, CIB, CIT. The results show that taken both mechanical and economic factors into consideration, the new material with configurations of MALECON_1A, MALECON_1B are more efficient in flexural and buckling load cases than that of traditional mono steel. MALECON could be a feasible alternative to metal in tower sections of OWT, which are sensitive to the flexure and buckling loads, especially for the new generation of offshore wind turbines. However, care should be paid to the conditions when structures would undertake a kind of considerable tensile load during his construction or service life. Sensitive analyses also show that the new material MALECON has obviously efficiency especially when the metal price is increasing.

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