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Ship Matrix-Deck and Analysis of Its Mechanical Properties

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Abstract. Ship deck is generally made of steel materials. With the development of ship technology and the demand of ship lightweight design, a lightweight and modular ship deck is needed. In this paper, a ship deck is designed based on the form of matrix; The deck is mainly made of engineering plastics and filled with load-bearing materials. The overall strength of the material is analyzed by FEM simulation. According to the simulation results, the compressive strength of this grid composite structure is basically equivalent to that of C30 concrete, but the weight can be reduced by 30% compared with C30 concrete The matrix-deck has the characteristics of high strength and low density, and is suitable for occasions with high requirements for material strength and material quality.

1. Introduction

Polyphenylene oxide(PPO) is a high-strength engineering plastic developed in the last century, which has good comprehensive properties, but the manufacturing process is complex[1]. The strength and thermal stability of pure PPO will deteriorate over time. In order to solve this problem, PPO and high impact polystyrene (HIPS) are usually mixed to obtain modfied polyphenylene oxide(MPPO). Stack[2] analyzed the thermal stability of PPO materials and MPPO; The results shows that the thermal decomposition temperature of MPPO is significantly higher than PPO; The reason is that HIPS molecules interrupt the molecular transfer in the high temperature decomposition of PPO, so as to improve the overall thermal stability of the material. HIPS is a highly elastic material, and its elastic deformation has strong nonlinearity.

Bucknall[3] proposed a method to quantitatively study the toughening of HIPS according to the characteristics of HIPS. By comparing the transverse and longitudinal strain components of HIPS under high tensile stress, the contribution mechanism of each component leading to HIPS deformation is determined; The results show that the deformation of HIPS under high tensile stress is mainly composed of elastic deformation and crazing.

Foam concrete(FC), which is made of blowing agent in ordinary concrete, has the characteristics of low density. It is widely used as a non-load bearing material in engineering. Because of the existence of pores of FC, modeling of FC is very difficult. Nambiar[4] analyzed the influence of porosity, permeability and pore size on the strength of FC. A series of experiments were carried out to study the effect of the above parameters on the strength and durability of the FC. The results show that the porosity, permeability and pore size affect the strength and density of the FC, while the shape of the pores has no effect on the strength of the FC. And fitting the function relationship of each parameter on the strength of FC. Zuhua Zhang[5] is used to study the thermal stability and energy saving of FC. The potential scale effect of FC in application is analyzed. Due to the difficulty in controlling manufacturing process and performance degradation process of the FC, the foamed concrete can not be widely used at present. Zuhua Zhang had proposed a method to control the quality and degradation process of FC, which could effectively reduce the uncertainty of FC characteristics in manufacturing process. His research findings can make the degradation process modelable, and the degradation process predictable, which greatly improve the usability of FC in engineering. WANG Hui[6] proposed a new type of FC. The new FC can be used for filling materials in large-span soft rock tunnels. Because of its low density, it can effectively reduce the settlement of the tunnel crown and greatly improve the stability and reliability of the tunnel. The research of WANG Hui shows the feasibility of foamed concrete as filling material in practical engineering, which has good reliability and durability.

Nambiar[7] in subsequent studies found that the type and radius of aggregate had a significant effect on the strength of FC. The smaller the radius is, the higher the strength of FC. The higher quality of the aggregate, the greater strength/density ratio. In order to further reduce the density of FC, Patchara Onprom[8] verified the feasibility of using coal ash instead of sand as aggregate. Using different proportion of coal ash instead of sand to make FC test blocks, The test results show that adding coal ash in FC can significantly reduce the density of FC and increase its water absorption. But the compressive strength of FC will decrease correspondingly. Shaohai Wang[9] directly used the graphite schist with radius of 0.1mm as the aggregate to manufacture FC. The results show that the strength/density ratio is medium and have obvious weight reduction effect. By adding animal angle particles in FC, Dong L[10][11] significantly reduced the manufacturing cost of FC, and the FC had good strength. The above three studies show that the composition of the aggregate has great influence on the performance of FC. Selecting the material with small density, small particle size and high strength as the aggregate of FC can significantly improve the comprehensive performance of FC. According to the high strength of MPPO and the low density of foamed concrete, a composite structure of light weight plate is proposed. The plate is designed for ship's deck, which has the characteristics of high reliability and durability; The weight of the ship can be effectively reduced by replacing traditional steel deck with this plate.

2. Design of composite structure

The overall structure of the plate is shown in Fig. 1. Its surface and subface are asymmetric design. Fig. 1(a) is the structural diagram of the subface; The main load-bearing structure of the plate is a grid MPPO frame; There are several rectangular cavities between the frame; The cavity is filled with FC. Because the cost of MPPO material is much higher than that of FC, this design can reduce the cost and density of the plate greatly under the condition that the strength of the plate does not decrease.

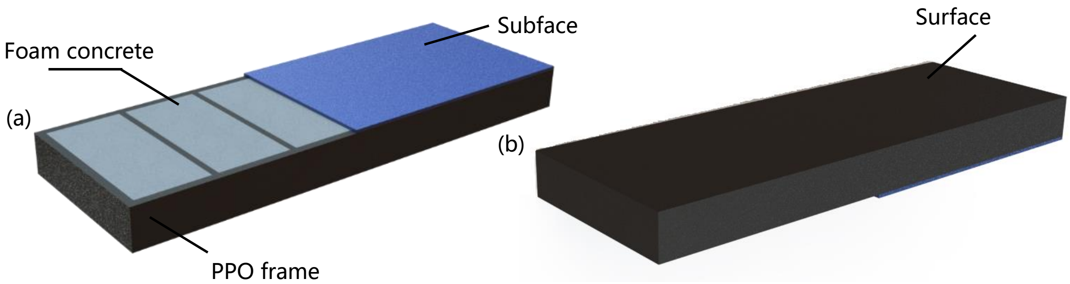

Fig. 1. Schematic diagram of the composite plate's structure.

The surface of the plate is a MPPO plate integrated with the frame, as shown in Fig. 1(b). After the MPPO frame is filled with FC, the polyurethane wear-resistant coating is sprayed on the surface and subface. After the coating is solidified, a complete plate is completed. In order to show the internal structure of the plate in Fig. 1, only half of the polyurethane coating is drawn on the subface.

The structural design with asymmetric subface and surface has the following advantages. First, because the compressive strength of FC is only 1-2Mpa, if the polyurethane wear-resistant coating is sprayed directly on the surface of FC, when the coating is subjected to pressure, the pressure of the polyurethane coating can not conduct well due to the small thickness and flexibility of the polyurethane coating. Then, FC will be subjected to a large concentrated stress, resulting in the destruction of FC. In order to solve this problem, the asymmetry design of the subface and the surface is put forward. A MPPO plate is added to the surface which is directly under pressure, so that the pressure can be transferred unimpeded to the frame, and the stress concentration of the FC is eliminated. As a non-bearing face, the subface does not need to add MPPO plate, which reduces the production cost and density.

3. Force analysis of the plate

3.1. Mechanical property modeling of FC

In order to establish the mechanical model of FC, the pores' distribution of FC is first described. According to[7][11], it is generally believed that the pores of the FC conform to normal distribution. The mathematical expression of its distribution is as follows[7]:

$$R(x)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(x-\mu)^2}{2\sigma^2}},(0<x<+\infty) \quad (1)$$

Where *R(x)* represents the probability of occurrence of pores with radius of *x*; *x* is the radius of the pore; μ and σ are the expectation and variance of normal distribution.

The bubble content of FC should also be expressed. The porosity can be obtained by the ratio of the density of non gas containing hardened slurry to that of gas containing hardened slurry[11]:

$$\omega=1-\frac{\rho}{\rho_0} \quad (2)$$

Where ω is porosity; ρ is the density of gas hardened slurry; ρ_0 is the density of non gas hardening slurry. By converting the normal distribution expression into the standard probability density formula:

$$R(x<X\le x+\Delta x)=\phi\left(\frac{x+\Delta x-\mu}{\sigma}\right)-\phi\left(\frac{x-\mu}{\sigma}\right) \quad (3)$$

When $x=0$:

$$R(0<X\le \Delta x)=\phi\left(\frac{\Delta x-\mu}{\sigma}\right)-\phi\left(\frac{\mu}{\sigma}\right) \quad (4)$$

Assunming the number of pores per unit volume is *m*, the following expression can be obtained[7]:

$$\sum_{i=1}^{\infty}\left\{\left[\phi\left(\frac{i\Delta x-\mu}{\sigma}\right)-\phi\left(\frac{(i-1)\Delta x-\mu}{\sigma}\right)\right]\cdot m\cdot\frac{\pi x^3}{6}\right\}=\omega \quad (5)$$

Assuming that porosity ω and normally distributed expectations μ and variance σ has following relationship:

$$\omega=f(\mu,\sigma) \quad (6)$$

Simultaneous formula(6), formula(5) and formula(2) can obtain:

$$\sum_{i=1}^{\infty}\left\{\left[\phi\left(\frac{i\Delta x-f^{-1}(\omega,\sigma)}{\sigma}\right)-\phi\left(\frac{(i-1)\Delta x-f^{-1}(\omega,\sigma)}{\sigma}\right)\right]\cdot m\cdot\frac{\pi}{6}\cdot\left[\left(i-\frac{1}{2}\right)\Delta x\right]^3\right\}=\omega \quad (7)$$

The pore distribution of FC can be obtained by this formula. The average pore's size and variance of FC can be calculated by this distribution. The pore's size of FC can be described more accurately. According to the formula of compressive strength of porous materials, the compressive strength of FC is as follows:

$$T=T_0(1-\omega)^{\beta} \quad (8)$$

T is the compressive strength of FC. T_0 is the compressive strength of concrete without foaming agent; ω Is porosity; β Is the compressive index, which is obtained by test.

3.2. Mechanical property modeling of MPPO

MPPO is a high polymer composite, and its mechanical properties are obviously different from ordinary molecular materials. The deformation of polymer materials is mainly creep and viscoelastic deformation. Creep is a phenomenon that the deformation of materials develops gradually with the passage of time under the action of a certain temperature and external force. The mechanical properties of polymer are closely related to its historical loads. In order to analyze the influence of historical load on MPPO deformation, Boltzmann superposition principle needs to be introduced. The principle is as follows: the deformation of polymer is a function of all historical loads; Each historical load has an independent contribution to the deformation, which satisfies the linear superposition principle. The total strain can be expressed as:

$$\varepsilon(t)=\sum_{i=1}^{n}\sigma_i J(t-\tau_i) \quad (9)$$

Where in $t=\tau_1,\tau_2 \ldots \tau_n$ applying discontinuous stress $\sigma_1,\sigma_2 \ldots \sigma_n$. If the stress changes continuously, the stress increment can be expressed by integral as[2]:

$$\varepsilon(t)=\int_{-\infty}^{t} J(t-u)\frac{\partial\sigma(u)}{u}du \tag{10}$$

Considering the lower integral limit, it is necessary to consider the whole history of polymers; However, in many cases, the tested polymer is not in the "zero state", so it is necessary to estimate its previous initial state, calculate its "zero state" response and "zero input" respectively, and then obtain the total strain of the polymer after superposition. Consider the scenario that the polymer is not in the "zero state". The total strain can be expressed as[2]:

$$\varepsilon(t)=\int_{-\infty}^{0} G(t-u)\frac{\partial\sigma(u)}{u}du+\int_{0}^{t} G(t-\tau)\frac{\partial\sigma(\tau)}{\tau}d\tau \tag{11}$$

The viscoelastic deformation of polymers is generally described by the constitutive model of materials. The commonly used viscoelastic models of polymers include Maxwell model, Kelvin Vogit model and Zener model. The three models are suitable for different viscoelastic scenarios; The specific selection needs to be determined according to the parameters of the material itself. No matter which model is adopted, the constitutive relationship of linear viscoelastic behavior is:

$$a_0+a_1\frac{d\sigma(t)}{dt}+a_2\frac{d^2\sigma(t)}{dt^2}+\cdots=b_0+b_1\frac{d\varepsilon(t)}{dt}+b_2\frac{d^2\varepsilon(t)}{dt^2}+\cdots \tag{12}$$

Through the constitutive model of polymer materials, the elastic strain under specific stress can be calculated; By accumulating the creep obtained in the early stage, the total strain of the polymer when a certain force is applied at a certain time can be determined.

4. FEM simulation results and analysis

According to the mathematical method in the previous chapter, the mechanical properties of MPPO and FC with regular shape can be analyzed; However, the composite structure proposed in this paper is complex, and there is a coupling relationship between MPPO and FC, which needs to be analyzed by FEM.

In this chapter, static FEM simulation is carried out for composite materials, and FEM simulation is carried out on MPPO frame, FC and whole panel respectively. The difference of the results proves the feasibility and rationality of the designed structure. The mesh type of FEM model is regular hexahedron; The cells' type are C3D10H. The boundary condition of PC and MPPO is "friction" and its friction coefficient is 1.5. The input load is uniformly distributed static pressure

4.1. Simulation results and analysis of MPPO frame

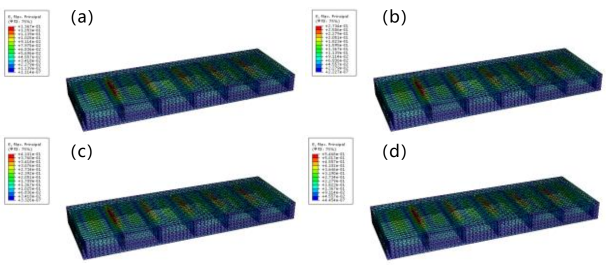

Fig. 2. FEM simulation of frame surface.
(a)10Mpa. (b)20Mpa. (c)30Mpa. (d)40Mpa.

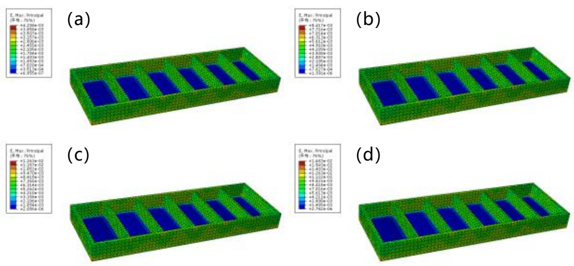

Fig. 3. FEM simulation of frame subface.
(a)10Mpa. (b)20Mpa. (c)30Mpa. (d)40Mp.

Fig. 2 shows the strain results of MPPO frame surface under stress. Apply pressure of 10, 20, 30 and 40Mpa to the frame surface respectively (Fig. 2(a)(b)(c)(d)); It can be seen from the results that the maximum strain of the frame is only 0.56mm under the pressure of 40Mpa; It is proved that the grid structure has sufficient strength, can effectively undertake the pressure from the surface, and has good force conduction. Fig. 3 shows the results when the frame subface directly bears pressure; Applying 10, 20, 30 and 40Mpa pressures to the subface respectively (Fig. 3(a)(b)(c)(d)). It can be seen that the cross section of the frame's wall is very small, so the strain is only 0.16mm under the pressure of 40MPa. In actual use, the subface is only used as the contact face which does not directly bear the pressure, so the subface also has good support performance.

4.2. Simulation results and analysis of the plate under stress on the subface

Fig. 4 is the strain diagram of the plate's subface under stress. Fig. 4(a), (b) and (c) show the strain of the coating when the pressure is 5, 10 and 20Mpa respectively. Fig. 4(d) (e) and (f) show the strain of internal structure when the pressure is 5, 10 and 20Mpa respectively.

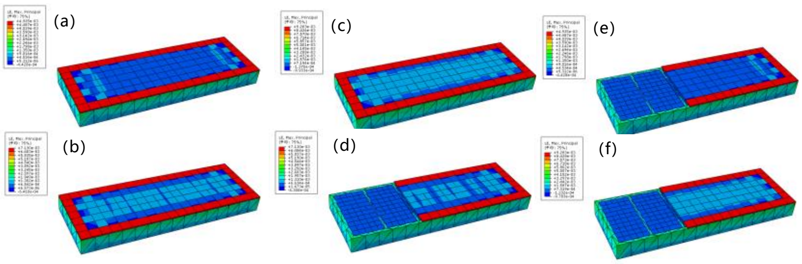

Fig. 4. FEM simulation of plate's subface. (a)5Mpa subface. (b)10Mpa subface. (c)20Mpa subface. (d)5Mpa internal. (e)10Mpa internal. (f)15Mpa internal.

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According to the FEM results, when the whole plate is under pressure; The boundary of plate coating will bear large stress, resulting in maximum strain. However, because the coating material is polyurethane which has flexibility. It can be seen that the edge strain is 0.01mm under the pressure of 20Mpa; It is much lower than the maximum strain of polyurethane material. The strain of the internal structure is far less than 0.01mm, and its main support is provided by MPPO; Foamed concrete only plays a role of filling. However, because polyurethane is an organic material, with the cyclic application of stress, its material may age and affect its mechanical properties. Moreover, if the load is not uniformly applied, the FC may be damaged due to the greater local stress. Therefore, this surface is not suitable for direct stress face; It is suitable for the supporting face at the bottom, which will not be subjected to a large concentrated stress, and the FC will not be destroyed easily.

4.3. Simulation results and analysis of the plate under stress on the surface

Fig. 5 and Fig. 6 show the FEM results when the surface of the plate is stressed. Fig. 5(a)(b)(c)(d) shows the surface strain at the pressure of 10, 15, 20 and 30Mpa respectively. Fig. 6(a)(b)(c)(d) shows the internal strain when the pressure is 10, 15, 20 and 30Mpa respectively.

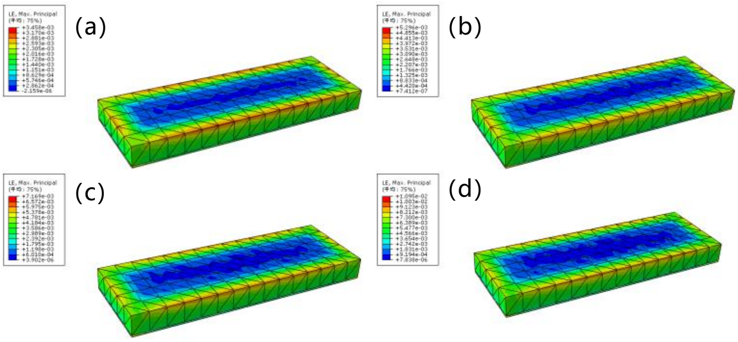

Fig. 5. FEM simulation of plate's surface.(a)10Mpa. (b)15Mpa. (c)20Mpa. (d)30Mpa.

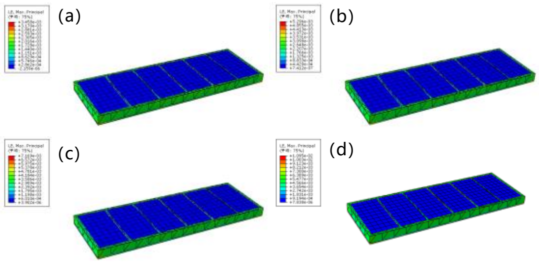

Fig. 6. FEM simulation of internal structure. (a)10Mpa. (b)15Mpa. (c)20Mpa. (d)30Mpa.

It can be seen from the FEM results that the strain of MPPO surface directly under pressure is also concentrated in the edge part, but its strain is significantly reduced. Moreover, it can be seen from Fig. 6 that the internal strain component is evenly distributed. It shows that the internal stress distribution can be significantly improved by adding 5cm MPPO plate on the frame. And the internal stress can be effectively reduced, so that FC will not be destroyed easily.

5. Summary

In this paper, a composite light plate is designed, and its mechanical properties are analyzed by FEM. The results show that the designed asymmetric subface and surface structure can significantly improve the stress distribution in the plate. In order to lighten the weight of the plate, the FC with light weight is filled. Because of the low strength and brittleness of FC, the stress in the plate is particularly important. Good structural design can effectively improve the internal stress distribution and reduce the mutation of internal stress, so as to protect the internal FC from failure. The simulation results in Chapter "FEM simulation results and analysis" can also strongly explain the above conclusion. In this paper, the feasibility of its structure is verified by FEM simulation, which provides the possibility for the lightweight design of non-metallic plates. The reliability and durability of the material need to be tested through experiments. This composite structure broadens the idea of composite plate design and provides a broad prospect for lightweight plate design in the future.

6. References

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