FE analyses and structural optimization on refitted floating container

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Abstract. On the basis of the requirements of river-crossing emergency traffic guarantee, a structural modification was exerted on 40-foot Dry Cargo Container. A structure of refitted floating container was designed, which could be used in the assembly of emergency floating bridge. A finite element method (FEM) theoretical analysis was made on the static strength and stiffness of refitted floating container. Two kinds of load levels were brought in as the typical working conditions. Modelling in the ANSYS circumstance to simulation analysis and accomplishing optimization design based on the results. The results show that the floating bridge system assembled by refitted floating containers can’t support the load under the level of wheel type-20 and crawler type-500 for a stress concentration appears on the contact sites between floating container and main girder. The maximum stress goes beyond the limit of yield strength. An structural optimization was made to eliminate the influence of stress concentration and floating bridge system assembled by refitted floating containers can meet the requirements of load level of wheel type-20 and crawler type-500 after optimization. The refitted floating container can play a role in transporting troops and engineering emergency task crossing the river in a short period of time.

1. Introduction
Bridge is the hub of transportation and difficult to repair in a short period of time if destroyed. So a floating bridge is usually erected in an emergency for the guarantee of the connection of the road. Floating bridge is a kind of bridge using boats or floating piers as its piers to provide bearing capacity. Floating bridge is an effective means to repair and build bridges in a short time [1-2].

Floating bridge can be divided into standard equipment bridge and expedient material bridge according to the source of erection equipment. Standard equipment refers to through the advance research and development design to produce a certain number of bridge support equipment having certain specifications and certain system, such as 67-type railway pontoon bridge and so on. Expedient material bridge refers to a simple temporary bridge erected with wood, steel, reinforced concrete culvert pipe and other easily available equipment. Due to the number of reserves, warehouse distribution, transportation performance and other reasons, the standard bridge equipment like military beam system can’t meet the requirements of rapid restoration of traffic lines. Expedient material equipment is needed as an effective supplement [3-4]. Container is a kind of large standardized storage vessel widely used in transportation industry which can be combined into a floating pier structure by means of expedient material, matching with other expedient material equipment or standard highway bridge equipment, can form bridge management support force in short time [5].
Much academic work has been done on pontoons and box structures. Wang simplified middle part of the 67-type railway pontoon bridge as continuous beam with elastic foundation. The static force of the pontoon bridge under dead load and class-18 live load is solved by using the basic theory of elasticity [6]. Liu and Guo proposed the structure unit of expandable floating tank based on the principle of expandable structure. Using ANSYS to simulate the bearing capacity of the structure unit and the optimal deck cross section inertia moment was obtained [7]. Shen divided the box structure into six simple laminated sheets based on the theory of elastic sheet. The distributed bending moment of four sides of each plate is solved by coordinating the corner Angle between plates and the analytical solution of the box structure under arbitrary load is obtained [8]. Chen used the finite element software Hyperwork to optimize the stiffness and carrying capacity of the container and took the strength and stiffness of the overall container as the objective function to optimize the overall container design [9]. Fan analyzed the calculation formula of the lateral stiffness of the whole container under uniformly distributed load and concentrated load and verified the theoretical analysis with the existing experimental data and Abaqus software [10]. However, there are few studies on the mechanical analysis of container as floating pier structure.

2. Structural design of refitted floating container

Refitting container to floating pier can retrofit used containers in advance and pre-install in the river bank which bridge repair and construction were needed. Due to the simple refitted process, containers can be refitted on site in case of emergency. The material is the most widely used 40-foot dry cargo container which external size is 12.20m×2.44m×2.59m, internal size is 11.85m×2.35m×2.38m, self-weight is 3.90t, volume is 58.60m³, main material is high strength hot wide strip(SPAH) [11].

Ordinary container does not have waterproof function. To make the container waterproof, Polystyrene foam (EPS) is filled inside the container by foaming technology in order to ensure that it can provide stable support force [12].

The assembling of refitted floating container and floating bridge girder can be fixed by welding. The combined structure of refitted floating container and girder is shown in Figure 1.

![Figure 1. Refitted floating container with girder.](image)

![Figure 2. Mechanical analysis model.](image)

3. Statics theoretical analysis

The refitted floating container structure bears the common load of floating bridge girder and vehicle. Because refitted floating container and girder joint is welding relationship, when the vehicle passes the floating bridge, bending moment is generated at the beam part, refitted floating container also has a certain amount of deformation.

In the process of actual loading, the main loading position of refitted floating container structure is the side wall plate. When the vehicle passes directly above the floating container, the internal force of
the refitted floating container reaches the maximum at the section with the girder, it’s a dangerous cross section [13]. The mechanical analysis model is established at the dangerous cross section.

The coordinate system is established with the centroid of the model’s dangerous section as the origin. The horizontal direction is the X-axis and the vertical direction is the Y-axis. The load is simplified as evenly distributed load $P$ between refitted floating container and girder. The component of $P$ along the X-axis is $P_x$ and the Y-axis is $P_y$. The mechanical analysis model of dangerous section is shown in Figure 2.

3.1. Section stress calculation
The refitted floating container structure is divided into finite block rectangular elements. The area of the dangerous section $A_s$ is [14]

$$A_s = \sum_{i=1}^{n} A_i$$

(1)

where $A_i$ is the area of rectangular element. Then the moment of inertia of the dangerous section $I_c$ can be expressed as

$$I_c = \sum_{i=1}^{n} I_i + \sum_{i=1}^{n} A_i y_{ci}^2$$

(2)

where $I_i$ is the moment of inertia of the rectangular element on the Y-axis. $y_{ci}$ is the coordinate value of the neutral axis of the $i$-th rectangular element.

Suppose the length of the upper side beam of the refitted floating container is $l$, the area of neutral axis away from $y_i$ relative to the moment of plane of the neutral axis is $S(y_i)$, then the normal stress $\sigma$ of the dangerous section at $y_i$ is

$$\sigma = P_s l y_i | I_c |^{-1}$$

(3)

The shear stress $\tau$ of the dangerous section at $y_i$ is

$$\tau = (2I_t l)^{-1} P_s I S(y_i)$$

(4)

where $t$ is the thickness of the side wall plate of the container.

The equivalent stress $\sigma_{eq}$ is calculated by the von Mises theory and it is

$$\sigma_{eq} = \sqrt{\sigma^2 + 3\tau^2}$$

(5)

3.2. Section deformation calculation
According to the structural characteristics of container refitted floating container, the dangerous section can be regarded as rectangular simply supported plate structure. The Angle constraint between plates is transformed into the distributed bending moment loaded on the plates. It is assumed that the upper and lower beam lengths of the rectangular simply supported plate structure are $a$ and $b$ respectively. The moment applied to each of the four sides of the plate is $f_1(x), f_2(x), f_3(x), f_4(x)$. The total deflection of the rectangular simply supported plate can be expressed as [8]

$$W(x,y) = W_1(x,y) + W_2(x,y) + W_3(x,y) + W_4(x,y)$$

(6)

where
\[
W(x, y) = \sum_{m=1}^{\infty} \frac{L_{m,a}^2}{2D(m\pi)^2} \left[ \alpha_m c \sin \left( \frac{m\pi(b-y)}{a} \right) - \frac{m\pi(b-y)}{a} \right] \sin \left( \frac{m\pi x}{a} \right) \tag{7}
\]

where \(\alpha_m = m\pi a^{-3}b, \quad L_{m,a} = 2 \int_0^a f(x) \sin \left( \frac{m\pi x}{a} \right) dx, \quad D\) is the stiffness of side wall plate of refitted floating container.

The Angle of rotation of the plate can be expressed as \(\partial W(x, y)/\partial x\) and \(\partial W(x, y)/\partial y\).

4. FE analyses

The plate surface of refitted floating container structure is simplified to a flat plate in the theoretical calculation, but the actual structure is corrugated steel, which will make the theoretical calculation results have a certain deviation. By using the finite element simulation software ANSYS, the structural characteristics of the refitted floating container can be better restored.

4.1. Modeling

According to the actual structure of refitted floating container, the model is established in CAD modeling software. See Figure 3. The model is imported into ANSYS and the lock rod, hinge, Angle column and other components are set as solid structure. The solid structure adopts four-node tetrahedral element SOLID285. The four-node quadrilateral shell element SHELL181 is used for the door and wall plate and the necessary Boolean operation processing is carried out to ensure a high degree of reduction in simulation analysis [15].

When the finite element model of refitted floating container is established, some simplified treatments are needed to facilitate the mechanical analysis [16]. It is mainly include: (1) Accessories which have no effects on mechanical properties of refitted floating container are not considered; (2) Chamfering, rounded corners and round holes far smaller than the overall size that do not affect the overall performance are removed; (3) Upper and lower side beam are simplified by element BEAM188; (4) The welding relation like the steel plate welding seam is simplified as binding contact, joint coupling and welding element; (5) Connect the force transfer part to do the necessary coupling processing of full degree of freedom. The model of refitted floating container after simplified treatment is shown in Figure 4.

![Figure 3. CAD model of refitted floating container.](image1)

![Figure 4. FEM model of refitted floating container.](image2)

4.2. Meshing and boundary conditions

The refitted floating container model is meshed by using the built-in meshing function of ANSYS. Select type Global for the element attribute and set the overall element size to 0.1. The boundary size of relatively complex parts was set at 0.05 to discretize the structural characteristics of the model. Shell and solid elements are generated by scanning [17].

The refitted floating container is loaded by both the girder and the passing vehicles. The passing vehicles are divided into wheeled vehicles and tracked vehicles which are simplified into concentrated
load and uniformly distributed load respectively according to the stress mode. The floating bridge girder adopts the assembled highway steel bridge structure composed of truss elements the material being mainly domestic steel 16Mn. It can meet the requirements of passing through equipment with wheel load less than 300kN and crawler load less than 500kN [18].

In actual working conditions, the refitted floating container is kept stable by the buoyancy of water and the pressure on the side wall. Therefore, the container bottom is set as a fixed boundary in the simulation. The material of the container is SPAH, the yield limit is 390~439MPa. The mechanical properties are [19]: Elasticity modulus $E = 2.06 \times 10^{11} \text{ Pa}$, Poisson’s ratio $\mu = 0.27$, density $\rho = 7900 \text{ kg/m}^3$.

According to the Chinese general specification for highway bridge and culvert design, wheel type-20 represents a single vehicle weighing 300kN or a fleet of vehicles weighing 200kN and crawler type-500 represents the tracked vehicle with a weight of 500kN [20]. The static simulation analysis of wheel type-20 and crawler type-500 was carried out respectively. The plasticity is based on the von Mises theory.

![Stress nephogram of refitted floating container](image)

**Figure 5.** Stress nephogram of refitted floating container: (a) Stress nephogram of wheel type-20; (b) Stress nephogram of crawler type-500.
4.3. Stress simulation analyses
Figure 5 shows the stress analysis results of refitted floating container under loading level wheel type-20 and crawler type-500.

According to the simulation results obtained, there is stress concentration at the contact between girder and floating container. Except for the stress concentration position, the stress of other parts of the container did not exceed 150MPa. If the safety factor \( n_b = 1.2 \), then the allowable stress is 325MPa. In the two load levels of the simulation, the maximum stress of wheel type-20 and crawler type-500 are 340MPa and 483MPa respectively, which exceeds the allowable stress of the material. Therefore, the strength of the refitted floating container structure can not meet the requirements of loading level wheel type-20 and crawler type-500, so structural improvement and optimization are needed.

4.4. Deformation simulation analyses
Figure 6 shows the deformation of refitted floating container at loading level wheel type-20 and crawler type-500.

![Deformation nephogram of refitted floating container](image)

**Figure 6.** Deformation nephogram of refitted floating container: (a) Deformation nephogram of wheel type-20; (b) Deformation nephogram of crawler type-500.
According to the simulation results, the side wall of the container is bent due to the vertical load under the two load levels. The central position deforms the maximum and the extreme value of crawler type-500 is the largest. Under the loading level crawler type-500, the maximum deformation of refitted floating container is 0.0025m and the total stressed height of the floating container is 2.59m, so the ratio of the deformation amount to the total stressed height is 0.097%, which is less than the allowable value 0.200%. Therefore, the stiffness of the refitted floating container meets the requirements when the vehicle equipment with loading level below crawler type-500 passes the floating bridge.

4.5. Comparison of theory and simulation results

The comparison of theoretical calculation results and simulation results under the two working conditions of wheel type-20 and crawler type-500 is shown in Table 1.

| Results          | Wheel type-20 | Simulation results of wheel type-20 | Crawler type-500 | Simulation results of crawler type-500 |
|------------------|---------------|------------------------------------|------------------|---------------------------------------|
| Max stress       | 352MP         | 340MP                              | 529MP            | 483MP                                 |
| Max deformation  | 2.06×10⁻³ m   | 1.78×10⁻³ m                        | 3.09×10⁻³ m      | 2.50×10⁻³ m                          |

It can be seen that the simulation results are close to the theoretical calculation results. Because the corrugated surface of container was not considered in the theoretical calculation, the results of the theoretical calculation were generally greater than the simulation results.

5. Structural optimization of floating container

According to the FEM simulation results of the refitted floating container structure, it can be seen that there is a stress concentration in the contact part between the refitted floating container and the girder and the maximum stress value is greater than the allowable value when the loading level is above wheel type-20 and crawler type-500. Therefore, it is necessary to strengthen the refitted floating container structure.

5.1. Structural optimization model

In order to solve the problem of insufficient strength of refitted floating container, a truss supporting structure which can be placed inside the container is designed. The member bar of the truss mainly bears tension or pressure so that it can give full play to the role of materials. The use of truss can save materials and reduce the weight of the structure. The tool based on zero order optimization method in ANSYS optimization module is used to determine the structure of the truss. The truss structure is i-beam and the supporting structure model is shown in Figure 7.
The dimensions of the supporting structure are strictly designed in accordance with the internal dimensions of the container, so that each side of the supporting structure can be close to the wall of the container, which can increase the support performance of refitted floating container and reduce the deformation of container body.

5.2. Check of structural optimization

According to the simulation results above, the extreme stress and strain of the structure of refitted floating container under the condition of loading level crawler type-500 are greater than that of loading level wheel type-20. Therefore, the optimized floating container structure is checked with the loading level crawler type-500 as the typical working condition.

The designed supporting structure is put into the interior of the refitted floating container for integral analysis. The stress and deformation results obtained under the loading level crawler type-500 are shown in Figure 8.

![Stress and deformation nephogram](image)

**Figure 8.** Stress and deformation nephogram of optimized refitted floating container: (a) Stress nephogram of crawler type-500; (b) Deformation nephogram of crawler type-500.
The simulation results show that the stress concentration on the optimized floating container is reduced after the supporting structure is added. With the maximum stress decreases, the deformation decreases correspondingly and the location of the maximum deformation also changes. The location is transferred from the two sides directly below the contact part between the floating container and girder to the middle position of contact part. The maximum stress of optimized floating container is 92MPa and it’s less than the yield limit of the material. The maximum deformation is $5.67 \times 10^{-4}$m and the structure meets the stiffness requirement.

The deformation at both ends of the floating container is small after optimized. Therefore, the length of the supporting structure can be reduced. The truss elements at both ends of the structure can be removed and the support can only be carried out in the middle of the floating container to reduce the overall mass of the refitted floating container.

The refitted floating container with improved supporting structure is simulated in ANSYS and the stress and deformation condition of refitted floating container at loading level crawler type-500 is calculated. The results are shown in Figure 9.

Figure 9. Stress and deformation nephogram of further optimized floating container: (a) Stress nephogram of crawler type-500; (b) Deformation nephogram of crawler type-500.
According to the simulation results, although the maximum stress of optimized floating container increases, it is still within the allowable range. The deformation at both ends of the floating container increases and the maximum deformation transfers from the middle of the floating container to the two sides. The structure meets the stiffness requirements. Therefore, the simplified supporting structure meets the design requirements. Table 2 shows the comparison of simulation results of refitted floating container without supporting structure, original supporting structure and simplified supporting structure.

| Simulation results | Without supporting structure | Original supporting structure | Simplified supporting structure |
|--------------------|------------------------------|------------------------------|--------------------------------|
| Maximum stress     | 483MPa                       | 92MPa                        | 137MPa                        |
| Maximum deformation| 2.50×10^{-3}m                | 5.67×10^{-4}m                | 8.47×10^{-4}m                |

6. Conclusions

(1) The composite floating bridge structure equipped with assembled highway steel bridge and refitted floating container does not meet the requirement of loading level wheel type-20 and crawler type-500. Stress concentration occurs at the contact part between refitted floating container and girder and the maximum stress exceeds the yield limit of the material. The refitted floating container structure needs to be optimized.

(2) The stiffness of the refitted floating container structure meets the design requirements under both loading level wheel type-20 and crawler type-500.

(3) The structural strength of refitted floating container can be improved by installing steel truss supporting structure inside the container. After optimization, the refitted floating container meets the loading level wheel type-20 and crawler type-500.

(4) The structure of the standard container was optimized to provide support in water. It can be used for the task of crossing the river in a short period of time in case of emergency and provide a new way of thinking for bridge support of expedient material bridge.

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