

Study and Optimization of Helicopter Subfloor Energy Absorption Structure with Foldcore Sandwich Structures

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Abstract. The intersection element is an important part of the helicopter subfloor structure. In order to improve the crashworthiness properties, the floor and the skin of the intersection element are replaced with foldcore sandwich structures. Foldcore is a kind of high-energy absorption structure. Compared with original structure, the new intersection element shows better buffering capacity and energy-absorption capacity. To reduce structure's mass while maintaining the crashworthiness requirements satisfied, optimization of the intersection element geometric parameters is conducted. An optimization method using NSGA-II and Anisotropic Kriging is used. A significant CPU time saving can be obtained by replacing numerical model with Anisotropic Kriging surrogate model. The operation allows 17.15% reduce of the intersection element mass.

1. Introduction

The subfloor structure is one of the most important structural components in helicopter energy-absorbing structures. So it has to be designed in order to limit the deceleration forces by structural deformation and provide post-crash structural integrity of the cabin floor [1]. Figure 1 shows a typical subfloor structure. In such a structure, the intersection elements play an important role in the overall crash response of the subfloor structure because of its high stiffness and strength. Experimental and numerical studies of intersection element are conducted by Bisagni C [1-4]. A fast reanalysis methodology based on neural network is proposed with the intent to reproduce the crash behaviour of structural intersections. Based on the methodology, size and topological optimization are conducted.

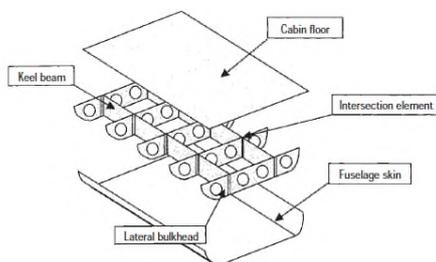


Figure 1. Typical subfloor structure.

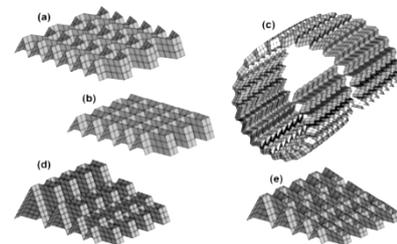


Figure 2. Some kinds of foldcore.

In order to increase the energy-absorbing capacity of the intersection element, structures with high energy-absorption capacity should be used. Foldcore sandwich structure is such a kind of structure. Foldcore, as shown in figure 2, are structures formed by folding plates or foils according to regular repeated lines. Foldcore sandwich structure has been studied a lot. The geometric design method and the

mechanics model of foldcore have been studied by Wang Z J [5, 6]. The energy absorption capacity of foldcore sandwich structures is studied by Zhang Y C. Due to their study, foldcore is proved to be a good anti-crash structure [7, 8]. Compression and shear experiments have been conducted on foldcore from CFRP and aramid paper by S. Heimbs [9-15]. The residual strength and the impact property of honeycomb core and foldcore sandwich structures have been studied with the help of experiments and numerical simulations.

Foldcore sandwich structures have been proved to have good energy absorption capacity. In this paper, an intersection element containing foldcore sandwich structures is designed and studied. And in order to reduce the intersection element mass while maintaining the crashworthiness requirements satisfied, optimization of geometric parameters is conducted.

2. Numerical simulation of the intersection element with foldcore sandwich structures

A typical intersection element is shown in figure 3. It is a drop experiment sample in paper [1]. The intersection element with foldcore sandwich structures can be got by replacing the skin and floor of the intersection element with foldcore sandwich structures. The floor is replaced with V-type foldcore sandwich structure and the skin is replaced with M-type foldcore sandwich structure. The new intersection element is shown in figure 4. The two kinds of foldcore are shown in figure 5. The simulation method of the foldcore sandwich structures are introduced in paper [16, 17]. In the simulation method, random geometric errors are introduced. The material used is aluminium alloy 2024 T3. The thickness of the foldcore sandwich structure plate t_c is 0.3mm and the thickness of the foldcore material is 0.15mm. The parameters of the foldcores are set as: $H_M=H_V=20\text{mm}$, $A_M=A_V=15\text{mm}$, $a_M=a_V=30^\circ$, $\lambda_M=\lambda_V=20$, $B_M=5\text{mm}$. The thickness of the rest panels are 0.81mm. The distance of the two mid-planes of the sandwich structures is 195mm. The impact velocity is 7.4m/s.

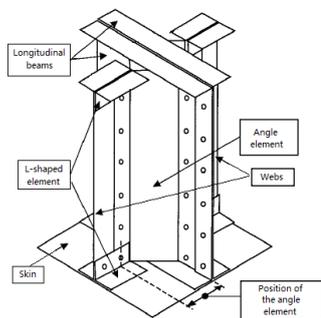


Figure 3. A typical subfloor intersection element.

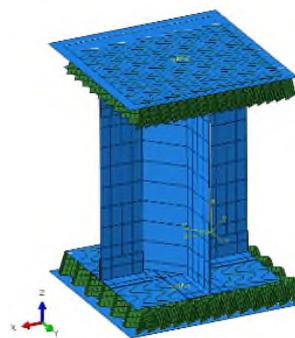
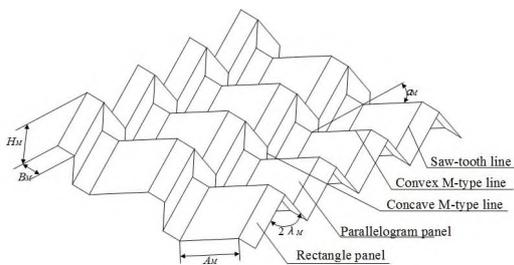
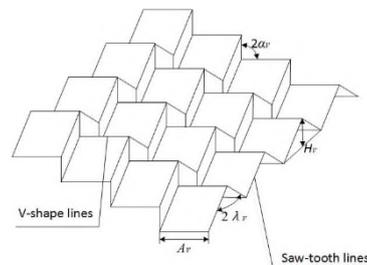


Figure 4. The intersection element with foldcore sandwich structures.



(a) M-type foldcore.



(b) V-type foldcore.

Figure 5. M-type and V-type foldcore and their geometric parameters.

In the numerical simulation model, the element type is chosen as 4-node shell reduced integration element S4R. The impact mass is 110kg and is applied on the middle of the floor top surface. Contact in the structure is modelled using ABAQUS general contact controls. The contact property is defined as “Hard” contact in the normal direction and penalty in the tangential direction with friction coefficient 0.17. The rivets are simulated by connecting nodes around the rivets of two panels using tie constraint.

The deformation process of the intersection element with foldcore sandwich structures is shown in figure 6. The crush analysis results of the new intersection element and the experiment result in paper [1] are shown in table 1. It can be seen that the structure with foldcore sandwich structures has smaller peak force and bigger crush force. It means that the structure with foldcore sandwich structures has better buffering capacity and energy-absorption capacity.

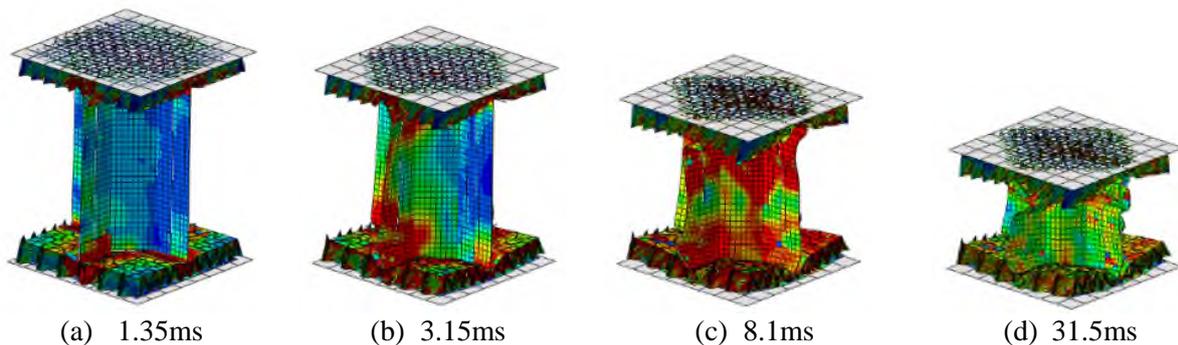


Figure 6. The deformation process of the intersection element with foldcore sandwich structures.

Table 1. Comparison of the intersection element with foldcore sandwich structures and typical intersection element.

| | Typical intersection element | Structure with foldcore sandwich structures | Variable ratio[%] |
|------------------|------------------------------|---|-------------------|
| Peak load[kN] | 52.0 | 41.9 | -19.4 |
| Average load[kN] | 22.7 | 26.8 | 18.1 |
| Mass[kg] | 0.481 | 0.480 | -0.2 |

3. Optimization of the intersection element with foldcore sandwich structures

In order to minimum the total mass while maintaining the crashworthiness requirements of the intersection element, geometric parameters optimization should be conducted, In this paper, an optimization method based on NSGA-II and Anisotropic Kriging is used. NSGA-II is chosen as the optimization algorithm. In each design point, the data needed are calculated through Anisotropic Kriging surrogate model, which greatly reduce the time cost of the calculation.

NSGA-II was improved from NSGA by Deb, Pratap and Agarwal. It can deal with optimization problems with both discrete and continuous variables. Besides, NSGA-II has good global searching ability due to its cross-operation. It means that NSGA-II can deal with optimization with irregular domain and complex constraints, which are just the characteristics of the optimization under crashworthiness requirements.

Anisotropic Kriging surrogate model is a kind of surrogate model which is based on statistical theory. In the numerical simulation model of foldcore, random geometric errors are applied in order to model the crashworthiness property more accurately. Besides, the importance of the geometric variables is different. The effectiveness of Anisotropic Kriging is not depending on the existence of random error. Anisotropic fitting technology is used in Anisotropic Kriging, which enables it to control the importance of the variables. So Anisotropic Kriging surrogate model is suitable.

The mathematical model of the optimization problem can be expressed as:

$$\begin{cases} \min & m(\mathbf{x}) \\ \text{s.t.} & \mathbf{x}_{\min} \leq \mathbf{x} \leq \mathbf{x}_{\max} \\ & A_{\max}(\mathbf{x}) \leq A_{\text{limit}} \\ & V_{\max}(\mathbf{x}) \geq 0 \end{cases} \quad (1)$$

In equation 1, $m(\mathbf{x})$ is the total mass of the structure, \mathbf{x} is the geometric parameter vector, $A_{\max}(\mathbf{x})$ is the maximum acceleration of the impact mass in z direction. A_{limit} is 48g, which is set according to MIL-STD-1290A (AV). V_{\max} is the maximum velocity of the impact mass. It should be noticed that the initial velocity is a negative value. The fourth formula in equation 1 means that the kinetic energy of the impact mass is totally absorbed. The range of variables is shown in table 2.

Table 2. Range of the design parameters in optimization.

| Parameter | A_M | a_M | λ_M | B_M | A_V | a_V | λ_V | t_c |
|---------------|---------|-------|-------------|---------|---------|-------|-------------|--------|
| Minimum value | 3.00mm | 15.0° | 10.0° | 3.00mm | 3.00mm | 15.0° | 10.0° | 0.3mm |
| Maximum value | 20.00mm | 65.0° | 45.0° | 10.00mm | 20.00mm | 65.0° | 45.0° | 0.5mm |
| Step | 0.02mm | 0.1° | 0.1° | 0.02mm | 0.02mm | 0.1° | 0.1° | 0.02mm |

Before optimization, Anisotropic Kriging surrogate model must be established. 200 intersection element models are established and analysed. Based on the analysis results, Anisotropic Kriging surrogate models expressing the relations of A_{\max} , V_{\max} and the geometric parameters are established. The total mass can be calculated as:

$$m = 0.305 + 0.14^2 \rho_{Al} \left[4t_c + \frac{B_M + A_M \sqrt{\sin^2 \lambda_M + \cos^2 \alpha_M \cos^2 \lambda_M}}{\sin \alpha_M (B_M + A_M \sin \lambda_M)} \delta_M + \frac{\sqrt{1 + \cot^2 \alpha_V \cos^2 \lambda_V}}{\sin \alpha_V} \delta_V \right] \quad (2)$$

25 intersection element models are used to check the accuracy of the surrogate model. The accuracy data of the surrogate models are shown in table 3.

Table 3. Error statistics of the Anisotropic Kriging surrogate models.

| Parameter | A_{\max} | V_{\max} | m |
|---------------|------------|------------|-------|
| Maximum error | 17% | 12.7% | 14.3% |
| Average error | 5.6% | 4.5% | 4.6% |

The accuracy of the surrogate models can meet the requirements.

The numerical simulation analysis of different intersection elements need CPU times from 1.5 hour to more than 12 hours. And with the help of Anisotropic Kriging surrogate model, one intersection element need only less than 1 second. Anisotropic Kriging surrogate model can greatly reduce the time cost.

NSGA-II is used as the optimization algorithm. In each generation there are 50 design points. After 60 generations, the optimization converges. The optimization results are shown in table 4.

Table 4. Optimization results.

| A_M [mm] | a_M [°] | λ_M [°] | B_M [mm] | A_V [mm] | a_V [°] | λ_V [°] | t_c [mm] | A_{\max} [m/s ²] | V_{\max} [m/s] | m [kg] |
|------------|-----------|-----------------|------------|------------|-----------|-----------------|------------|--------------------------------|------------------|----------|
| 10.10 | 65.0 | 35.5 | 8.10 | 7.62 | 64.5 | 35.5 | 0.30 | 443.42 | 0.7116 | 0.399 |

Compared with the original structural mass 0.481kg, mass of the optimized intersection element reduces 17.15%.

4. Conclusions

(1) The intersection element is an important part of the helicopter subfloor structures. The floor and skin of the intersection element are replaced with foldcore sandwich structures. The new intersection element shows good crashworthiness properties.

(2) An optimization method using NSGA-II and Anisotropic Kriging is introduced. NSGA-II can deal with optimization under crashworthiness requirements with irregular domain and complex constraints. Anisotropic Kriging can deal with models with random errors and can greatly reduce optimization time cost.

(3) After optimization, the mass of the intersection element with foldcore sandwich structures reduce 17.15% while all the crashworthiness requirements satisfied.

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