32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Design and Verification of Energy-absorbing Structure of Corrugated Beam Based on Specific Failure Mode

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Abstract

This paper presents a new structure design method of energy-absorbing composite corrugated beams. For the sake of yielding higher specific energy absorption result, a progressive failure mode of the corrugated beam was preseted, which is successively comprised by: local buckling in the straight section web of the composite waved beam at first, and then compression failure on the corner area, break off in the straight section and unload, and consecutively followed by a new failure circle. Base on this selection, the detailed size and layers of the corrugated beam was designed by using a semi-empirical method, and a group of experiments were carried out for validation. The proposed design method shows good accuracy by comparison between the design load and experiment results, and the progressive failure processes of the corrugated beam are also in good accordance with the predicted ones.

Keywords: helicopter, crashworthiness, composite corrugated beam, energy absorption.

1. Introduction

Military helicopters are usually equipped with energy-absorbing components at the bottom of fuselage for crashworthiness. The energy-absorbing components are generally composed of laminated corrugated beam made of composite materials. At present, tremendous experiment works has been carried out to optimize the profile and dimensions of the energy-absorbing structures, which requires a long development time at a high cost.

In this paper, a progressive failure mode of corrugated beam is selected, and the structure dimension is determined through theoretical calculation to ensure that only the preset failure would occur, so as to control the energy absorbing effect. Three groups of corrugated beam with continuously optimized dimensions were consecutively tested to validate the structure design.

2. Corrugated beam configuration and failure mode

2.1 Corrugated beam configuration

The corrugated beam is composed of web and upper and lower protruding edges (see Figure 1). The cross-section of the web is typically sinusoidal. In order to facilitate production, a simplified configuration consisting of triangular waves and filleted corner is selected, which is similar to sine wave. Its waveform is shown in Figure 2.

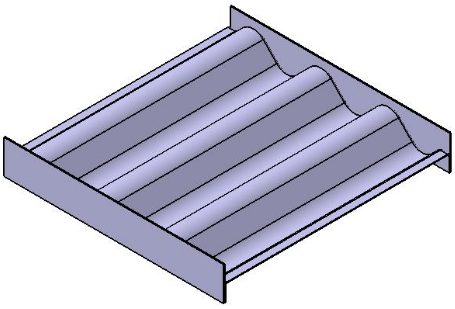


Figure 1 – A schematic model of corrugate beam.

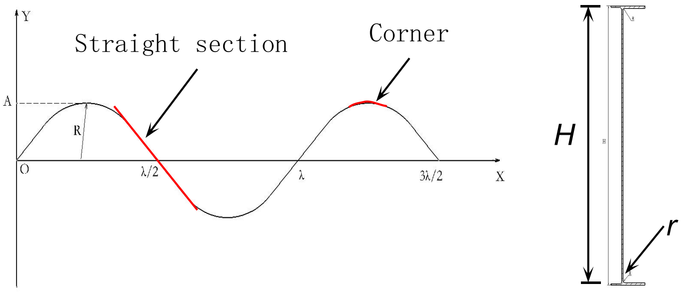


Figure 2 - The profile of sinusoidal corrugated beam

The main dimensions of corrugated beams include: height (*H*), wavelength (λ), amplitude (*A*), radius of filleted corner (*R*), thickness (δ) and radius (*r*). In order to reduce the peak load of corrugated beam during the impact, a weak link on the foot of web (namely *r*-area) is intentionally designed with less layers than other area.

2.2 Failure mode selection

The failure strength of the layer is related to the failure strength of the resin matrix. Local buckling is related to the modulus, thickness, size and support conditions of the material. The compression loss and failure of the corner region are related to the modulus, thickness, size and compression failure strength of the material. The compression failure value is depend on the material strength, which is highly dispersed for composite material. In ordr to obtain relatively reliable energy-absorbing devices, failure mode such as local buckling that is not related to the tensile and compressive failure strength is selected intentionally. Therefore, the following whole-process failure mode is selected:

At first, the straight section web occurs local buckling, and then angular compression damage, and then straight web break and Load drop, and then local buckling of the straight web, and that cycle repeats. The load-displacement curve shows as Figure 3.

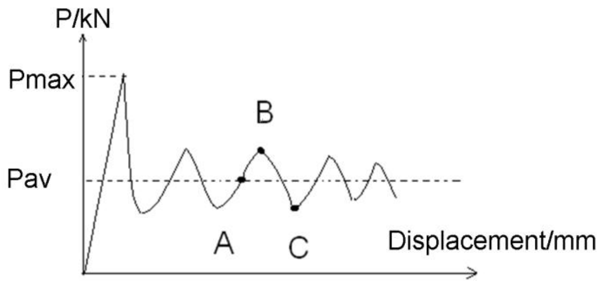


Figure 3 - A schematic load-displacement curve of laminated composite corrugated beam

Here， Pmax represents the max force when the corrugated beam damged process, Pav denotes the average force when the corrugated beam damged process.

2.3 The condition and calculation method of expected failure mode

In order to fulfill the preseted failure mode of the corrugated beam as described in section 2.2, the following conditions shall be met:

$$P_g > P_L \tag{1}$$

where P_g denotes the general buckling force, P_L denotes Local buckling force, and at r-area：

$$P_f \le P_b \tag{2}$$

Where, P_f denotes flexural failure force, P_b denotes bonding failure force.

The corrugated beam with 3 sines is taken as the research object, according to the aircraft design manual[1]:

$$\sigma_g = \frac{\pi^2 CEI_{min}}{SH^2} \tag{3}$$

$$\sigma_{\mathrm{L}} = \frac{K\pi^2 E}{12\left(1-\mu^2\right)}\left(\frac{\delta}{b}\right)^2; \tag{4}$$

$$\sigma_{\mathrm{crippling}} = C_{\mathrm{s}}\sqrt{\sigma_{\mathrm{b}} E}\,(\frac{\delta}{b})^{0.75} \tag{5}$$

Where, σ_g denotes general bucking stress, σ_L denotes Local bucking stress.

Now, C is the end support coefficient, here C=1; K is the critical strain coefficient of local buckling. Here, K=3.6; C_s is the support coefficient at both edges of the corner, calculated as the non-free edge. Here, C_s =0.366; E is the equivalent modulus of the corrugated beam; μ is the equivalent Poisson's ratio of the corrugated beam; σ_b is the compressive strength limit of composite materials; b is the length of the web of the section of the corrugated beam, and here:

$$b = \sqrt{4A^2 + \lambda^2/4} \tag{6}$$

S is the sectional area of the corrugated beam, here,

$$S = \delta\sqrt{16A^2 + \lambda^2}$$

(7)

$I_{\min}$ is the minimum moment of inertia of the section of the corrugated beam. Here,

$$I = f_1(A,\lambda,\delta) = \frac{4}{3}\delta A^2\sqrt{A^2 + \lambda^2/16} \tag{8}$$

So, the various failure loads of the corrugated beam under the axial compression load are as follows：

$$P_{\mathrm{g}} = \sigma_{\mathrm{g}} S = \frac{\pi^2 E A^2 \delta\sqrt{16A^2+\lambda^2}}{3H^2} \tag{9}$$

$$P_{\mathrm{L}} = \sigma_{\mathrm{L}} S = \frac{K\pi^2 E\delta^3}{4(1-\mu^2)\sqrt{A^2+\lambda^2/16}} \tag{10}$$

$$P_{\mathrm{crippling}} = \sigma_{\mathrm{crippling}} S_1 = 0.366 S_1\sqrt{\sigma_{\mathrm{b}} E}\,(\frac{\delta}{\sqrt{4A^2+\lambda^2/4}})^{\frac{3}{4}} \tag{11}$$

According to the composite material design manual[2], the shear stress between the laminates of composite material subjected to the transverse force (P) and the bending caused by it is calculated as follows:

$$\tau_{\mathrm{xz}}^{(k)} = \frac{P\cdot\Sigma_{i=k}^{n} E_x^{(i)} S_i}{B\cdot\overline{EI}} \le \tau_{\mathrm{b}} \tag{12}$$

so，

$$P_{\mathrm{bonding}} = \frac{\tau_{\mathrm{b}}\cdot B\overline{EI}}{\Sigma_{i=k}^{n} E_x^{(i)} S_i} \tag{13}$$

Where, $\tau_{xz}^{(k)}$ is the interlayer shear stress at the interface of layer k and layer $k+1$; $E_x^{(i)}$ is the elastic modulus of the ith layer in the x direction; S_i is the static moment of the cross-sectional area of the ith layer between z_k and z_n relative to the neutral axis y; $\overline{EI}$ is the bending stiffness of the cross section to the neutral axis y, here,

$$\overline{EI} = \int_A E_x^{(i)} z^2 \mathrm{d}A = \sum_{i=1}^{n} E_x^{(i)} I_y^{(i)} \tag{14}$$

B is the width of the laminated beam:

$$B = 12\sqrt{A^2 + \left(\frac{\lambda}{4}\right)^2} \tag{15}$$

$I_y^{(i)}$ is the moment of inertia of the cross section of the ith layer with respect to the neutral axis y.

The bending destructive force in the induced *r*-area:

$$P_{\text{bending}} = \frac{\sigma_{\text{bending}} W}{r + \delta / 2} = \frac{\sigma_{\text{bending}} b\delta^2}{6r + 3\delta} \tag{16}$$

3. Corrugated beam design

3.1 Crash-resistant design objectives

According to the crash-resistant design guide[3], the maximum and average acceleration should not exceed 51g (recommended 48g) and 24g respectively with 95% survival probability. The following is calculated according to the vertical crash energy required by the body mechanism to absorb 9.051m/s.

3.2 Selection of parameters (Sample 1)

Carbon fiber composite material of high temperature resin 5224 system was selected as the corrugated beam material, and the parameters were preliminarily selected according to the process implementation requirements: H = 400mm, λ = 120mm, R = 25 mm and r = 3mm.

According to engineering experience, the failure mode has a local post-buckling failure (with stratification), and its energy absorption ratio per unit mass is relatively low, about 30-50 J/g. Then, according to the energy theory:

$$E = mE_{\text{m}} = k_{\text{L}} L\delta h\rho E_m = Lm_i a_{\text{av}} h \tag{17}$$

The mass of Corrugated beam shall bear per unit length, According to the statistical value of the target model: m_i=800 kg/m; Height of structural space H=400mm, and average acceleration a_{av}=24g. The volume density of composite prepreg 5224/CF3052/39 is 1639kg/m^3, and the volume density of 5224/U-1360/37 is 1521kg/m^3. An average value of them is chosen as the laminate density ρ (which is 1580kg/m^3). For general sinusoidal corrugated beam, the wavelength/chord length ratio is K_L=1.5. So we can decuce:

$$\delta = \frac{m_i a_{av}}{k_L \rho E_m} = \frac{800 \times 24 \times 9.8}{1.5 \times 1580 \times E_m} \tag{18}$$

So, $\delta \in$ [1.58, 2.64]mm, and a median value of 2.11mm is selected as the initial thickness value.

The initial thickness is 2.11mm, and carbon fiber-reinforced prepreg 5224/ CF3052/39 (denoted as C1) is adopted, then 7 layers are needed, and a layer of glass cloth 5224/EW110C (denoted as G) is added on each surface as the surface protection. For conventional laminate, the layup is G(45)/C1(45)/C1(45)/C1(0)/C1(0)/C1(0)/C1(45)/C1(45)/G(45). If the effect of strain rate on modulus is ignored, the equivalent young's modulus E=41100MPa, poisson's ratio μ= 0.37, and the thickness δ = 2.195mm. The cladding in the Angle inducing area of the corrugated beam is: G(45)/C1(45)/C1(0)/C1(45)/G(45).

The equivalent Young's modulus E is 35,000MPa, Poisson's ratio μ is 0.437, and the thickness δ equals to 1.055mm. The allowed shear stress between layers of corrugated beam is 60MPa, according to formula 13, P_{bonding}=21530N. According to formula 16, the bending failure force in the induced Angle area, P_{bending}=17043N. Therefore, bending failure occurs in the induced Angle area first.

Based on the conditions under which the expected destruction occurs: $\sigma_g \geq \sigma_L$,so one can obtain:

$$\frac{\pi^2 E A^2}{3H^2} \geq \frac{\pi^2 E}{3(1-\mu^2)} \left(\frac{\delta^2}{4A^2 + \lambda^2 / 4}\right) \tag{19}$$

so A ⩾ 14. In fact, in order to ensure that local buckling occurs preferentially, the value of A is usually taken to be large, at least 1.5 times. So here, A = 20.

3.3 Compliance analysis of theoretical value

Take the local buckling load as P_{av}. According to formula 10,P_{av}=123940N. The maximum load Pmax was taken as the compression damage and failure load in the web corner area. According to formula 11, it can be seen that: P_{max}=187000N. According to the overload requirements of Section 3.1, the destructive power of sample 1 does not meet the crash-proof design indexes, so the thickness and the layer of sample 1 should be reduced.

3.4 The parameters of Sample 2 and 3

Calculate iteratively according to the above steps until the designed corrugated beam conforms to the index. The results of the corrugated beam are shown in Table 1.

Table 1 - Designed corrugated beam confirms.

Parameters	Corrugated beam 1	Corrugated beam 2	Corrugated beam 3
H,mm	440	440	440
λ, mm	120	120	120
A, mm	20	20	20
R, mm	25	25	25
r, mm	3	3	3
Layers	G(45)/C1(45)/C1(45)/C1(0)/C1(0)/C1(0)/C1(45)/C1(45)/G(45)	G(45)/C1(45)/C1(0)/C1(0)/C1(0)/C1(45)/G(45)	G(45)/C1(45)/C1(0)/C1(45)/C1(0)/C1(45)/G(45)
δ,mm	2.195	1.625	1.625
layer(r-area)	G(45)/C1(45)/C1(0)/C1(45)/G(45)	G(45)/C1(45)/C1(0)/C1(45)/G(45)	G(45)/C1(0)/C1(45)/C1(0)/G(45)
δ (r-area)	1.055	1.055	1.055
P_{max},kN	187.0	116.5	124.0
P_{av}, kN	123.9	51.8	56.0

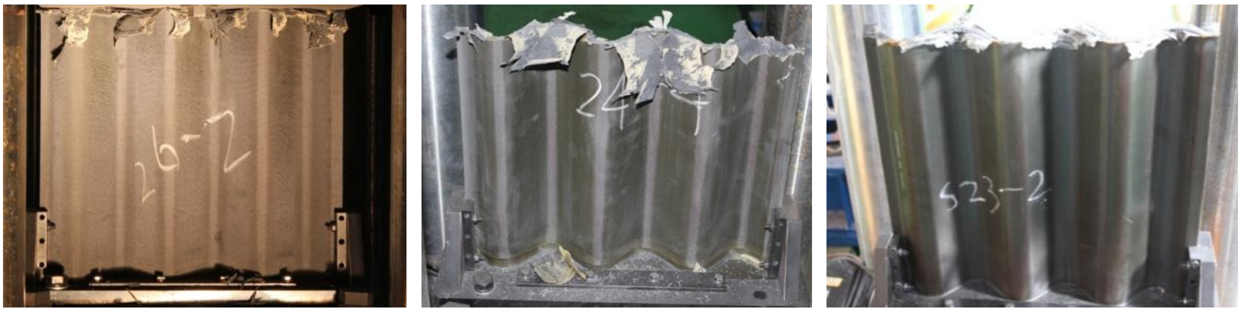
4. Verification of impact test of corrugated beam

4.1 The test results

According to the information in Table 1, 3 kinds of test pieces were manufactured with 6 pieces for each type. The test was completed on the impact test platform. The test data of the three corrugated beam test pieces can be seen in Table2 , Figure 4 and Figure 5.

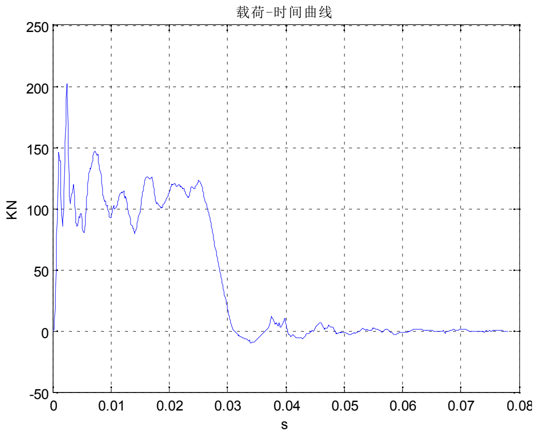
Table2 - The test data of the three corrugated beam test (Unit: kN).

		Sample1	Sample2	Sample3	Sample4	Sample5	Sample6	Average
Corrugated beam 1	P_{max}	209.3	211.8	232.5	202.3	182.7	208.6	207.9
	P_{av}	112.9	111.6	113.4	108.2	110.4	113.6	111.7
Corrugated beam 2	P_{max}	137.4	146.8	138.6	172.1	172.3	212.2	148.1
	P_{av}	78.3	66.6	61.6	69.2	69.2	67.3	68.7
Corrugated beam 3	P_{max}	162.7	156.2	145.5	119.0	146.0	181.0	151.7
	P_{av}	74.0	89.0	72.0	71.0	58.0	74.0	73.0

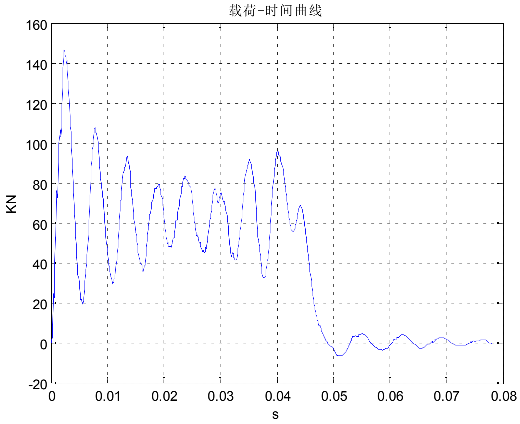


(a) Corrugated beam 1 (b) Corrugated beam 2 (c) Corrugated beam 3

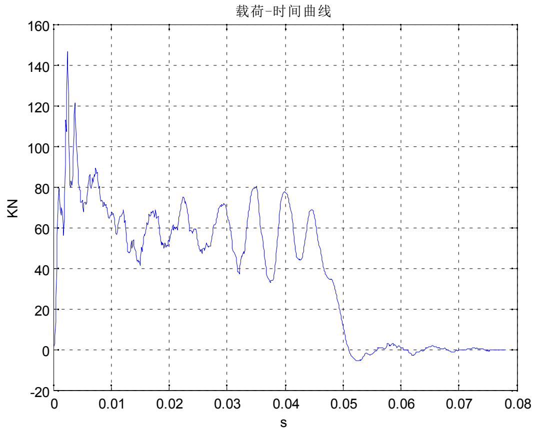
Figure 4 - Typical photoes of corrugated beam after impact tests



(a) Corrugated beam 1



(b) Corrugated beam 2



(c) Corrugated beam 3

Figure 5 - The typical impact load-time curves of different corrugated beam

4.2 Test results and analysis

4.2.1 Test failure mode verification

Judging from the test results, none of the corrugated beams showed unstratified failure and subsequent failure. From the load-time curve of the test piece, continuous stability failure occurs when the load rises to Pmax. It can be determined that the corrugated beam is destroyed according to the established failure mode.

4.2.2 Failure load deviation analysis

The deviation between the test value and the calculated value comes from two aspects: the deviation between the real size of the test piece and the theoretical size; The accuracy of the strength value of the material used in theoretical calculation. The thickness of the test pieces was measured, which is mostly fulfill the requirements of ±5% deviation, and a considerable part of the thickness deviation reached 6.5%. The test parts were tested within 2 months after manufacturing, and the test parts were not fully damp-heat aged, so the theoretical calculation should take into account the environmental impact factor of 1.2 times. The theoretical calculation considering the deviation of thickness ±5% and the environmental impact of the material is shown in Table 3.

Table 3 - Calculated value intervals.

	P_{max}, kN		P_{av}, kN	
Corrugated beam 1	top limit	244	top limit	154
	low limit	171	low limit	114
Corrugated beam 2	top limit	152	top limit	76
	low limit	106	low limit	47
Corrugated beam 3	top limit	162	top limit	69
	low limit	113	low limit	51

It can be seen that the test results lie in the upper and lower limits of the calculated values after considering the thickness deviation and material strength deviation. Furthermore, the calculation formula used in this paper is verified and have moderate accuracy.

5. Conclusion

This paper present a new design method for energy-absorbing corrugated beam based on the macro-failure mode. Formulae predicting critical load of compression damage for metal structures is adopted, which simplified the design process of corrugated beam. Following conclusions can also be drawn:

1. the progressive failure processes of the corrugated beam are in good accordance with the predicted ones, and the designed corrugated beam 2 and 3 meet the crash-resistance requirement;
2. The calculation formula adopted in this paper is verified and the accuracy is acceptable;
3.The test results also show that the manufacturing accuracy of corrugated beam has a decisive influence on its performance.

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