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Effect of Spring-in Deviation on Fatigue Life of Composite Elevator Assembly

Hua Wang[1,2]

Abstract The spring-in deviation results in the extra stresses around the joints of the composite C-beam and metallic parts when they are assembled together. These extra stresses affect the composite elevator's fatigue life, which should be explored with the fatigue experimentation. The paper presents the experimental investigation on the effect of spring-in deviation on the fatigue life of the composite elevator assembly. The investigation seeks to build the relationship between the spring-in and the fatigue life in order to determine the spring-in threshold during the course of assembling. The phenomenological model of the composite C-beam is constructed to predict the stresses around the joints. Based on the predicted spring-in induced stresses around the joints, pre-stresses are precisely added to the fatigue specimen when conducting the fatigue experiment. At last, the relationship curve of the spring-in on the composite C-beam's fatigue life is obtained from the experimental data. Giving the fatigue life accepting limits, the maximum accepting spring-in deviation during the course of assembling could be obtained from the relationship curve. The reported work will enhance the understanding of assembling the composites with spring-in deviation in the civil aircraft industry.

Keywords Composite C-beam · Fatigue life · Spring-in · Pre-stress

1 Introduction

Composite elevator is one important assembly in the aircraft. It is mainly composed with the metallic and composite components: the nose ribs, the forward spar, the metallic joints, ribs and the skin panels. The forward spar, a kind of Carbon Fiber Reinforced Plastic/Polymer

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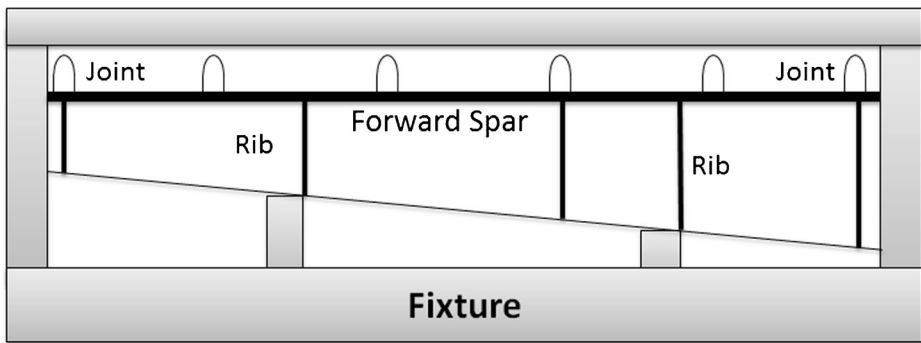
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(CFRP) C-beam, forms the front structures of the elevator. The forward spar is cured hot. There are residual stresses in laminates because of the mismatch of thermal expansion along and across the fibers, cure shrinkage of the thermoset resin and the change from cure to room temperature. When the forward spar comes out of the mould, there are spring-in deviations (Fig. 1) in it which should be properly handled in the following assembling process [1–3].

The spring-in results in the interference in the structure when the spar and metallic parts are being assembled together (Fig. 1). The assembling with the interferences will introduce the extra stresses around the joints and the structure. These extra stresses affect the composite elevator's fatigue behavior, which could be explored with the fatigue experimentation. The test specimens are subjected to fatigue loading according to the certain standards, such as some standards from the ASTM (American Society for Testing and Materials). The manufactured CFRP part differs from its nominal state by the spring-in deviation. The existing fatigue experimentation standards consider the nominal state of the specimens without considering the extra-stresses induced by the spring-in deviation. It is important to precisely add the extra stresses induced by the spring-in to the specimen when conducting fatigue experiments. Because inadequate fatigue failure prediction can lead to conservatively-designed assembling processes, which amount to efficiency and weight penalties in aircraft structures assembling.

The paper investigates the effect of spring-in deviation on fatigue life of composite elevator assembly. The investigation seeks to build the relationship between the spring-in and the fatigue life in order to determine the spring-in threshold during the course of assembling. After discussing the most relevant literature, typical assembling process of the composite elevator with the spring-in is analyzed. In order to predict the stresses around the joints, the phenomenological model of the forward spar, that is the composite C-beam, is constructed and verified. Standard fatigue experiments are carried out based on the ASTM's available standard to determine the composite C-beam's fatigue life with the spring-in deviation. Based on the predicted spring-in induced stresses around the joints, pre-stresses are precisely added to the fatigue specimen in the fatigue experiment. At last, the relationship curve of the spring-in on the composite C-beam's fatigue life
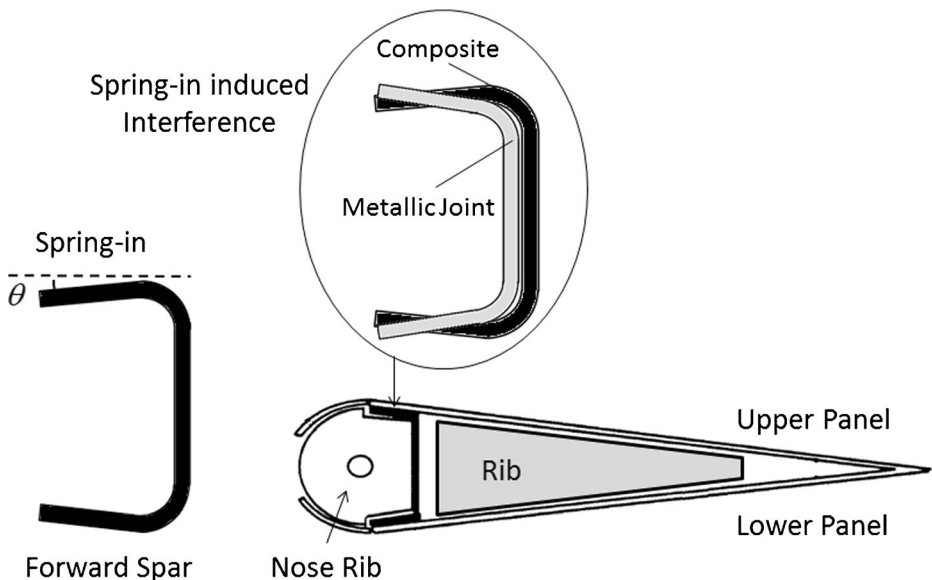
Fig. 1 Composite elevator and the spring-in deviation

Fig. 2 Composite elevator assembling fixture

is obtained from the experimental data. Giving the fatigue life accepting limits, the maximum accepting spring-in during the course of assembling is obtained from the relationship curve.

2 Literature Review

Due to cure and thermal shrinkage, a decrease of the enclosed angle in the composite C-beam is inevitable and it is referred as the spring-in or the springforward phenomenon [4]. Spring-in is a common problem which causes difficulty and expense for composite manufacturers. A number of experimentations were performed to explore the parameters which may affect spring-in [5]. Mould angles in the spring-in zone are modified to compensate for the spring-in. The 'rules-of-thumb' or trial-and-error from past experience [6] is the references for the amount of modification. Jareteg [7] reported a process variation simulation method for composite parts and assemblies with spring-in deviations for geometry assurance. Wang [8] reported a phenomenological model of the composite C-beam to predict the first failure location and the corresponding loading when assembling. Wang [9] studied the effect of spring-in deviation on a bimaterial beam's ultimate tensile strength with the numerical model and experimentation. Wang [10] conducted the tolerance simulation of composite wingbox assembly considering the spring-in deviation. The original distribution of the spring-in deviation modified with the clamping forces when conducting the wingbox assembling.

Beside the ultimate tensile strength, the fatigue behavior is another important aspect should pay attention to when assembling the composite C-beam with the spring-in. Smith [11] proposed a concept for an efficient, automated liquid shimming system and to verify the feasibility of specific components of the system. Comer [12] conducted thermo-mechanical
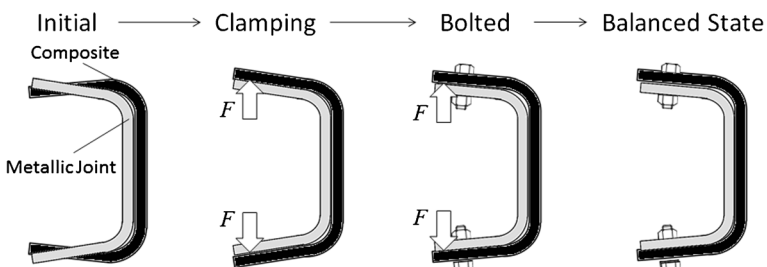

Fig. 3 Forward spar assembling with the metallic joint in interference state
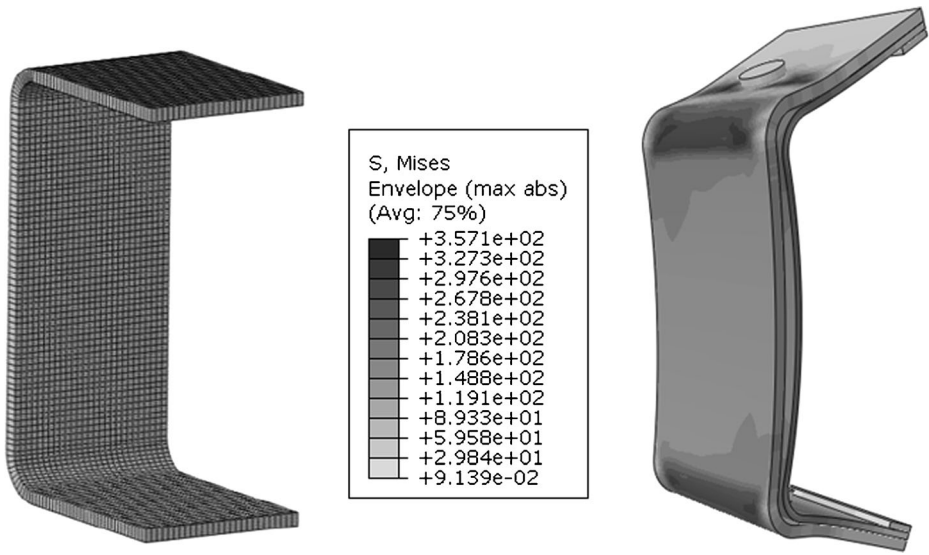
Fig. 4 Phenomenological model of the composite C-beam

fatigue analysis of liquid shim in mechanically fastened hybrid joints for aerospace applications. Franco [13] investigated the mechanical performance of hybrid double-lap AL-GFRP bonded-bolted joints by using experimental analyses and numerical simulations. Ghafoori [14] conducted finite element analysis for fatigue damage reduction in metallic riveted bridges using pre-stressed CFRP plates. The effects of the un-bonded post-tensioning method with different pre-stress levels on fatigue susceptibility are explored. Ghafoori [15, 16] employed the constant life diagrams to determine the minimum level of CFRP pre-stress required extending the fatigue life of existing metallic beams. By applying a compressive force to an
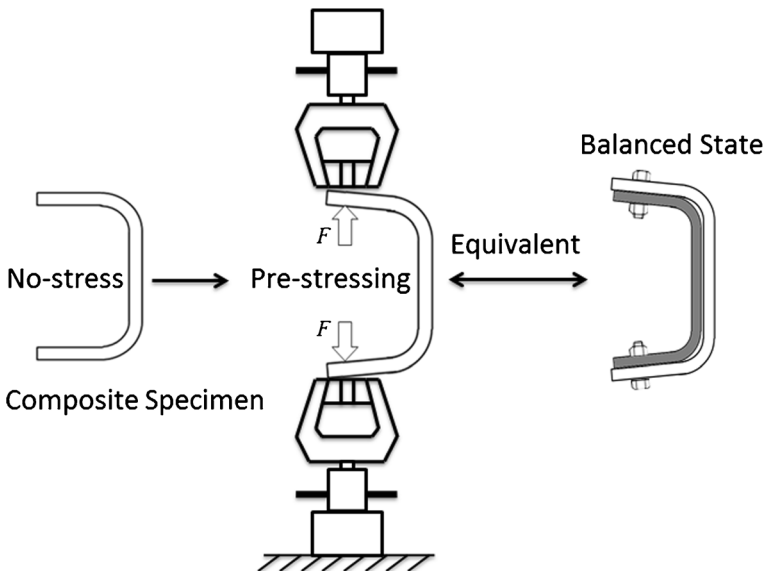
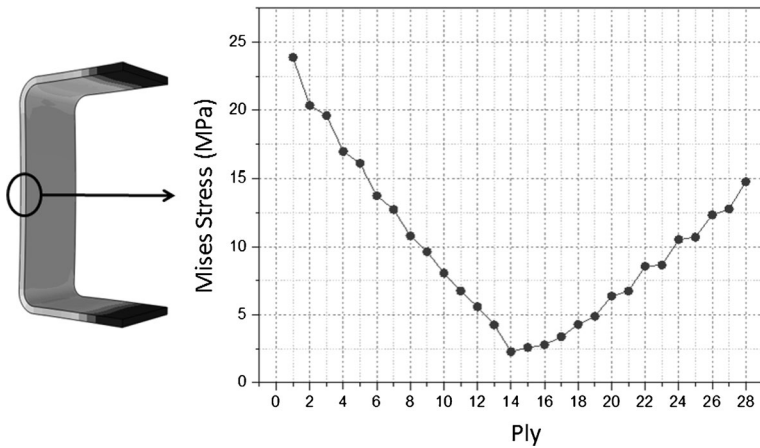**Fig. 5** Pre-stressing in the composite C-beam specimen

Fig. 6 Composite C-beam's stresses along the thickness

existing fatigue-susceptible detail using pre-stressed CFRP plates, the mean stress level can be reduced such that the detail is shifted from the 'finite life' regime to the 'infinite life' regime. Wicaksono [17] reported the test set-up and results of the woven CFRP structure life prediction subject to static and fatigue loading. The proposed "stiffness decay" model was applied to predict the onset of initial failure and the progression towards final failure.

3 Composite Elevator Assembling

Composite elevator is one important assembly in the aircraft. It is composed with the metallic and composite components: the nose ribs, the forward spar, the metallic joints, and the skin panels etc. The major assembly operations are conducted in the fixture (Fig. 2). The fixture precisely locates and holds the forward spar, ribs and metallic joints during the course of assembling.
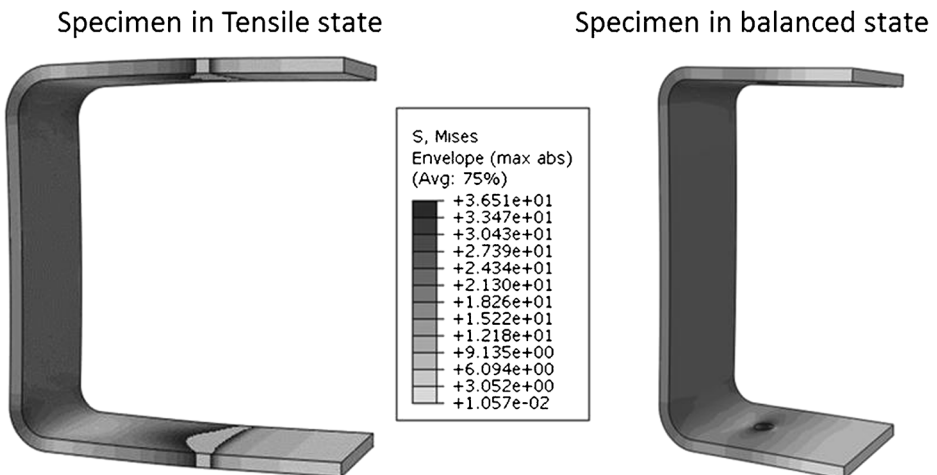

Fig. 7 Stresses of the specimen in the tensile state and the balanced state

Table 1 Composite C-beam's von Mises stresses (unit: MPa)

Point	Ply 1			Ply 14			Ply 28		
	T	B	Δ	T	B	Δ	T	B	Δ
1	23.87	21.38	10%	2.58	2.48	4%	14.79	13.43	9%
2	23.65	21.11	11%	2.56	2.44	5%	14.16	13.28	6%
3	21.29	20.39	4%	2.42	2.2	9%	14.41	14.74	2%
…	…	…	…	…	…	…	…	…	…
69	18.52	18.25	1%	1.87	1.85	1%	18.12	18.31	1%
70	18.66	18.32	2%	1.86	1.84	1%	17.11	18.56	9%
Average	19.82	19.19	5.9%	2.28	2.02	8.3%	17.56	16.96	7.7%

T represents the Tensile state, B represents the Balanced state, Δ represents Difference

Due to the manufacturing deviations, there are interferences or clearances between the detail parts. Once detail parts are positioned and clamped properly, holes in each of the mating surfaces are drilled, and then fasteners are installed. When there are interferences/clearances in the fit-up positions, prescribed clamping forces are applied to eliminate the small gaps between the mating surfaces (Fig. 3). The practical handling of interferences/clearances will introduce the extra stresses to the structure. These extra stresses affect the composite elevator's fatigue life, which should be explored with the fatigue experimentation.

The major concerning surfaces are the forward spar to the metallic joints because these are the areas that extra-stresses concentrated. After sealing and quality assurance inspection, the assembled composite elevator is ready for delivery. When it is taken out from the fixture, the assembled structure endures a balancing process and comes to a state with balanced stresses. The assembling process of the forward spar in the interference state is shown in Fig. 3.

4 Spring-in Induced Stresses

In order to predict the stresses around the joints, the phenomenological model of the composite C-beam (Fig. 4) is constructed in commercial software ABAQUS and it consists of 28 CFRP layups. The composite C-beam is meshed with 8-node, 3D solid, reduced integration C3D8R continuum three-dimensional elements with hourglass, and the proposed model was verified with the experiment data [8].

The stress field of the composite C-beam in the balanced state is the experimental stress state when conducting the fatigue experiments. That is to say, the fatigue specimen should contain the extra stresses in advance the same as its stresses of the balanced state. It is referred as pre-stresses in the paper. Pre-stressing means to add the extra stresses induced by the spring-in to the specimen when conducting the fatigue experiment. As far as the interference state is concerned, the fatigue specimen

Table 2 Mechanical properties of single-layer CFRP

| E_1(GPa)	E_2(GPa)	v_{12}	G_{12}(GPa)	X_T(MPa)	X_C(MPa)	Y_T(MPa)	Y_C(MPa)	S(MPa)
139	9.5	0.3	6.5	2600	1250	26	140	70

Table 3 The tensile cyclic experiments' load conditions

Experiment	Nominal load	Pre-stressing	Real load	Equivalent R-angle
1	0–1.5 kN	0 kN	0 kN-1.5 kN	90°
2	0–1.5 kN	0.4 kN	0.4 kN-1.9 kN	87°
3	0–1.5 kN	−0.4 kN	−0.4 kN-1.1 kN	93°

should be pulled to some extent in order to contain the pre-stresses in advance the same as the stresses of the assembled composite C-beam with the metallic joint (Fig. 5).

Taking the composite C-beam assembled with the metallic joint [8, 9] as the example to demonstrate the precision pre-stressing process, the composite C-beam's phenomenological stresses are linearly distributed along the thickness (Fig. 6). The phenomenological stresses in the ply 1, 14 and 28 are chosen for precision pre-stressing. Seventy points in the designated region are chosen for pre-stressing (Fig. 7 and Table 1).

Precision pre-stressing criterion includes each difference and the average of the difference between the tensile state and the balanced state. All differences should be less than 10%, allowing the differences of no more than 5% points greater than 10%. Based on the data comparison in Table 1 and the precision pre-stressing criterion, the assembled composite C-beam (whose R-angle is 87°) in the self-balanced state is equivalent to the state of the specimen (whose R-angle is 90°) being pulled with 0.4kN. That is to say, the specimens should be pulled with 0.4kN force in advance when conducting fatigue experiments. Similarly, the assembled composite C-beam (whose R-angle is 93°) in the self-balanced state is equivalent to the specimen (whose R-angle is 90°) being pushed with 0.4kN. The specimens should be pushed with 0.4kN force in advance when conducting fatigue experiments.
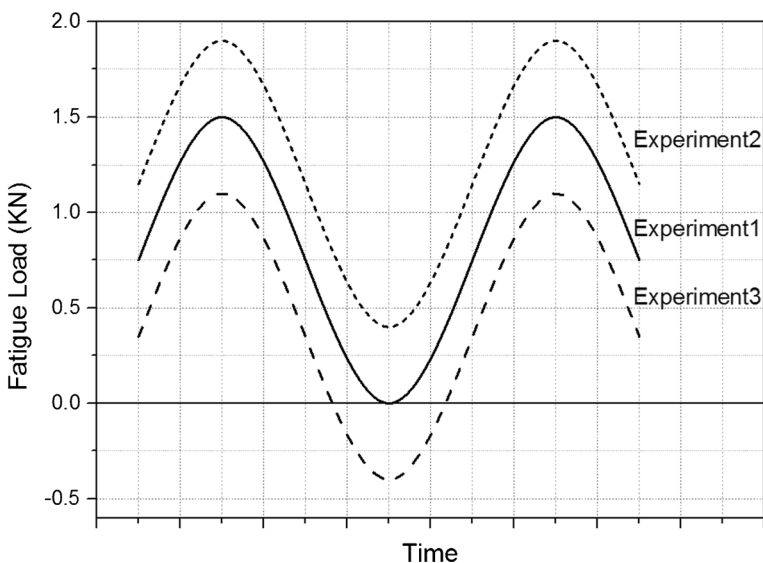
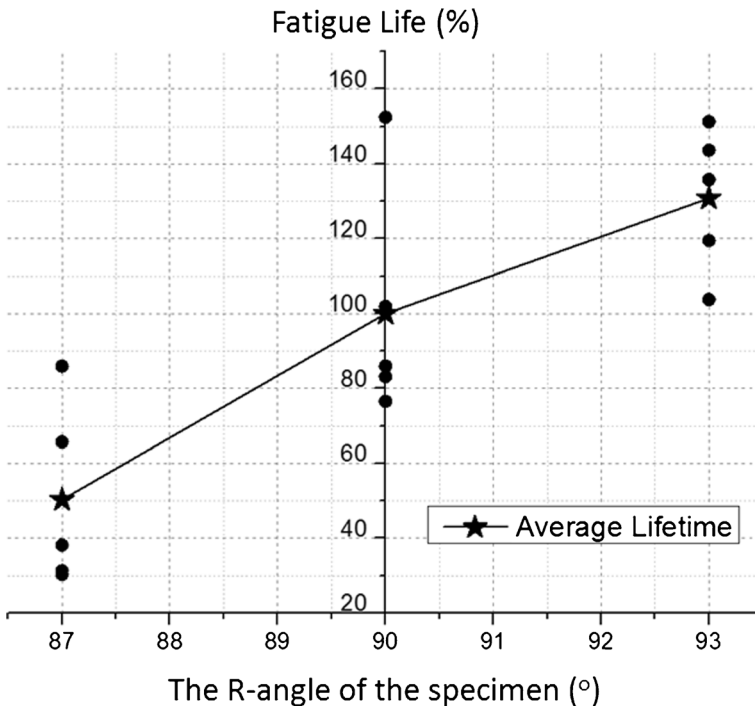
Fig. 8 The tensile fatigue loads

Table 4 The tensile fatigue experiment results

Experiment	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
1	35708	32875	65494	36935	43784	42959
2	13013	36918	16372	13427	28211	21588
3	64990	44573	61700	51314	58329	56181

5 Materials and Fatigue Experiments

Fifteen composite specimens with 90° R-angle are designed and fabricated for pre-stressing fatigue experiments. The laminate is fabricated using carbon-fiber (Toray T700) substrate with a $[+45°/-45°]_{7S}$ stacking sequence, and the laminate nominal thickness is 3.38 mm. Epotech 3325A/B epoxy resin is infused into the lay-up using a proprietary resin infusion technique. The mechanical properties of single-layer CFRP are shown in Table 2 [18].

The pre-stressing fatigue experiments are carried out in a 50kN servo-hydraulic Shimadzu EHF-U series fatigue machine. Pull & push fatigue experiments are conducted to evaluate the pre-stressing fatigue behaviors of the specimen. The tensile cyclic experiments are performed under load control at frequency of 3 Hz and a load ration of R = 0 in dry conditions at 25 °C. The applied maximum tensile force in cyclic loading is 1.5kN, which corresponded to 60% of the ultimate tensile strength in quasi-static loading of the composite specimen [9]. This stress level assures a low risk for run-outs and too few cycles to failure with a static-like failure. Failure in fatigue is defined as the total loss of laminate load carrying capability. Table 3 and

Fig. 9 Effect of spring-in on the tensile fatigue life of the specimen

Table 5 The compressive cyclic experiments' load conditions

Experiment	Nominal load	Pre-stressing	Real load	Equivalent R-angle
4	-1kN to 0kN	0 kN	-1kN to 0kN	90°
5	-1kN to 0kN	−0.4 kN	−1.4kN to −0.4kN	93°

Fig. 8 present the maximum and minimum loads applied to the specimen, and the amplitude of cyclic loading for the pre-stressing fatigue experiments.

Experiment 1 represents the nominal assembling of the composite C-beam without the spring-in deviation. Experiment 2 represents the assembling of the composite C-beam with the spring-in deviation -3°. Because the specimen (whose R-angle is 87°) in the balanced state is equivalent to the state of the specimen being pulled with 0.4kN. Experiment 3 represents the assembling of the composite C-beam with the spring-in deviation +3°. Because the composite C-beam (whose R-angle is 93°) in the balanced state is equivalent to the state of the specimen being pushed with 0.4kN. Each experiment is conducted with 5 specimens. The fatigue experiment results are shown in Table 4 and Fig. 9.

The compressive cyclic experiments are performed under load control at frequency of 3 Hz and a load ration of $R = 0$ in dry conditions at 25 °C. The applied maximum compressive force in cyclic loading is 1.0kN, which corresponded to 60% of the ultimate compressive strength in quasi-static loading for the composite C-beam [9]. For the experiment 4 in Table 5, it represents the nominal assembling of the composite C-beam without the spring-in deviation. For the experiment 5 in Table 5, it represents the assembling of the composite C-beam with the spring-in deviation +3°. Because the composite C-beam (whose R-angle is 93°) in the balanced state is equivalent to the state of the specimen being pushed with 0.4kN. The real fatigue load became (−1.4kN to −0.4kN). The fatigue experiment data are shown in Table 6 and Fig. 10.
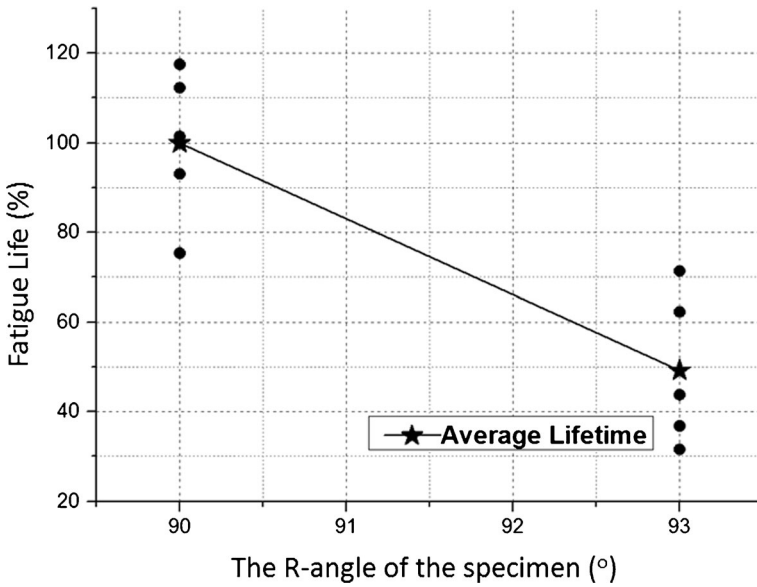
The effect of spring-in deviation on the fatigue life of the composite C-beam should consider both the tensile fatigue performance and the compressive fatigue performance. Combining Figs. 9 and 10, the effect of spring-in deviation on the composite C-beam 's fatigue life is shown in Fig. 11.

6 Conclusions

The paper reported the experimental investigation on the effect of the spring-in deviation on the fatigue life of composite elevator assembly. The phenomenological model of the composite C-beam was constructed to predict the stresses around the joints. Based on the predicted spring-in induced stresses around the joints, pre-stresses were introduced to the fatigue specimen precisely in the fatigue experiments. At last, the relationship curve of the spring-in on the composite C-beam's fatigue life was obtained from the experimental data. Giving the

Table 6 The compressive fatigue experiment results

Experiment	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
4	58719	43607	53860	64961	67978	57825
5	18275	21266	36045	25309	41303	28440

Fig. 10 Effect of spring-in on the compressive fatigue life of the specimen

fatigue life accepting limits, the maximum accepting spring-in deviation during the course of assembling could be obtained from the relationship curve. The reported work could enhance the understanding of the composites assembling with the spring-in deviation in civil aircraft industry.
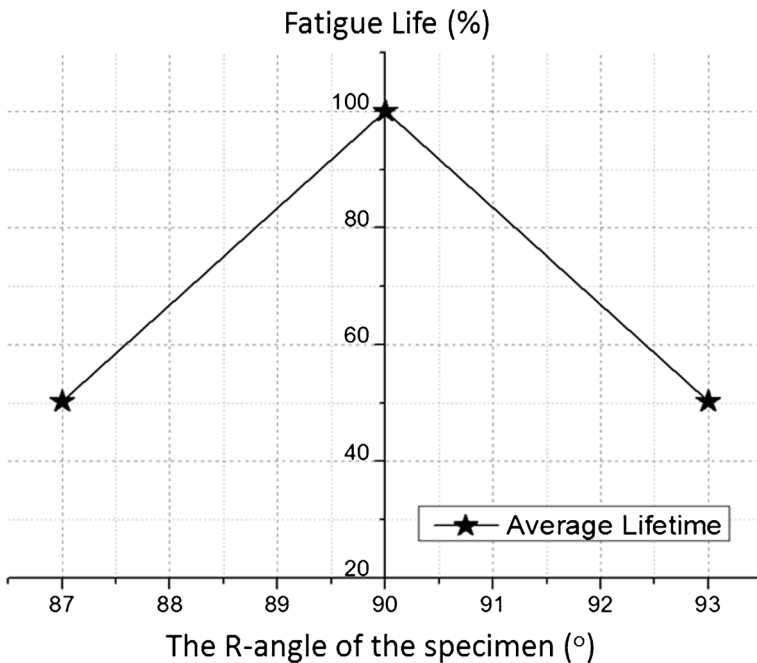
Fig. 11 Effect of spring-in on the fatigue of the composite C-beam

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