USING STRAIN GAUGES TO MONITOR BOLT CLAMPING FORCE AND FRACTURE IN COMPOSITE JOINTS DURING FATIGUE TESTS

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Abstract

This paper presents an effective method to monitor the loss of clamping force and detect crack initiation and propagation in the fasteners of composite bolted joints during lap shear fatigue tests using strain gauges and an algorithm to process the data. The location of the strain gauges was determined to make their readings suitably sensitive to the effect of the clamping force and to reduce the effect of the external load on the strain readings. The algorithm recognises the load cycles and, using the superposition principle, extrapolates the strain associated only with the clamping force for each cycle. The method has been validated numerically and experimentally. In the experimental results, the clamping force has been observed to remain constant for most of the joint fatigue life and, subsequently, to drop rapidly as the bolt failure progresses. It was further observed that there is a load transfer and an interaction between the bolts during the failure process, which is related to the fast but stable fatigue crack propagation that takes place in the bolts before final failure of the joint.

1 Introduction

Bolted joints have been widely used in the aircraft industry for many years and, even with the recent and widespread introduction of composite materials, still have a key role in aircraft structures. Bolt clamping force has a great importance on the behaviour and strength of bolted joints and safety of structures such as aircrafts. A considerable amount of joint failures are caused by a wrong estimation of bolt clamping force during installation or by an excessive clamping force loss during service. There is no direct way to measure bolt clamping force and, even though several indirect methods have been developed, this matter still proves to be challenging. In addition to this, the relation between clamping force loss, time and temperature has previously been highlighted [1] but the relation between clamping force loss and fatigue cycles is still to be investigated.

The easiest way to measure bolt clamping force is using a torque wrench. Even though this method is easy to implement, it has been proven to be very imprecise since it relies on an estimation of the coefficient of friction between nut and plate. A more sophisticated method uses strain gauges; these can be applied on either a bush located between nuts and plate [2] or directly embedded internally to the bolts [3]. This method has shown to be precise but needs a specific specimen setup (such as holes in bolts or additional bushes), which, in most of the cases, could modify the strength and behaviour of the specimen. More advanced methods involve the use of ultrasonic waves to acquire the length or the tension of bolts [4,5]. Even though the use of ultrasonic waves has shown promising capabilities to measure bolt clamping forces, the possible need of special specimen setup and the dependence of the readings on the bolt head and nut shape still limit its industrial application. More recent methodologies involve the use of interferometers [6] and digital image correlation techniques [7] to detect either the out-of-plane displacements or the strain of the plates. These methodologies do not require any modification to the specimen but, on the other hand, need to have a complex setup and have strict limitations on the type of specimen and test configurations that can be studied. Even though each of the methods mentioned has proven to work successfully for specific tests or applications, there is still the need for a new methodology developed to monitor the clamping force of bolted joints continuously during fatigue tests and without modifications to the specimens.

This paper presents an inexpensive and effective method to monitor the loss of clamping force and detect crack initiation and propagation in the fasteners of composite bolted joints during lap shear fatigue tests using strain gauges and an algorithm to process the data. It subsequently presents and discusses experimental results and identifies the stages of the process that leads to the final failure of the joint.

2 Methodology

The method proposed to monitor the bolt clamping force uses the readings of the external load applied to the joint (Fig.1) (from the machine's load cell), the data from a strain gauge located close to each bolt and an algorithm to post-process the data.

Fig.1. Specimen of a composite bolted joint for the fatigue single lap shear test.

Each strain gauge is located next to a bolt nut (Fig.2 and Fig.3) and is orientated perpendicularly to the main direction of the specimen. Two forces are applied to the specimen:

- clamping force of the bolts, which deforms locally the plates around the fasteners, applied during the assembly of the joint;
- cyclic external load, applied during the fatigue tests.

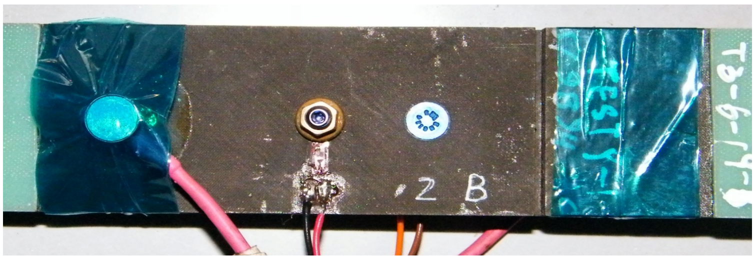

Fig.2. Specimen equipped with 2 strain gauges (and acoustic emission sensors not used in the presented method).

During the fatigue test, because of their particular position, the strain gauges read the changes in strain caused by both the applied external fatigue load and loss of clamping forces. Assuming that the recorded strain has an almost-linear response to the clamping force and to the external load, it is possible to apply the superposition principle. In this way, the total strain recorded is simply the sum of the strains related to the two forces.

To have clear readings of the strain related to the clamping force, it is necessary to subtract as much as possible the strain caused by the cyclic external load. This is possible if the location and the orientation of the strain gauges are properly selected and the strain is filtered using a suitable algorithm.

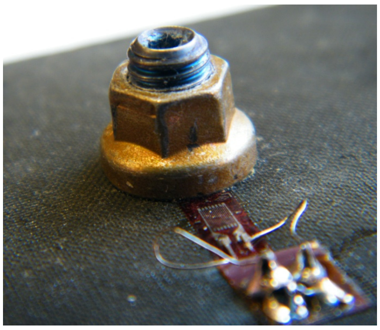

Fig.3. Location of the strain gauge.

The particular location and orientation of the strain gauges (Fig.2 and Fig.3) should allows them (1) to be sufficiently sensitive to detect the change in strain related to the local deformation of the plates due to the loss of bolt clamping force and (2) to reduce the effect of the external cyclic load on the readings. The location and the orientation of the unidirectional strain gauges have been selected using a previously developed numerical model of a composite bolted joint [8] with the same shape and dimensions of the specimens tested in fatigue. In Fig. 4, it is possible to see the model's mesh with the 8 nodes considered as possible locations for the strain gauges. Fig. 5 shows the strain in the radial direction for the 8 nodes during the phases of (i) Clamping force application, (ii) Initial ramp-up of the external load on the joint and the (iii) Ramp Down and (iv) Ramp up of the fatigue load cycle. Location 7 has been chosen because of the relatively high strain caused by the clamping force, the relatively stable response of the joint during the initial ramp up (non-linearity caused by the friction and the slipping of the plates [8]) and the limited variation of strain during the ramp up and ramp down compared to the strain caused by the clamping force. The numerical results confirm the validity of the assumptions highlighting the linearity of the strain vs. the clamping force and the external load during the fatigue cycle and the degree of superposition of the effects.

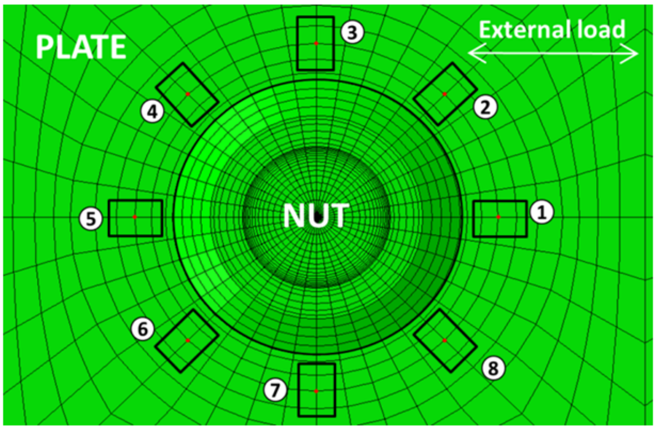

Fig.4. Eight positions analysed as possible locations for the strain gauge.

The data from the strain gauges and from the load cell is recorded simultaneously in order to know the level of external load applied to the specimen for every strain reading. The sampling frequency needs to be significantly higher than the frequency of the applied load and, in particular, high enough to study the variation of the strain during the load cycle. In general, the higher the recording frequency, the more effective the algorithm will be in filtering the strain related to the cycling external load.

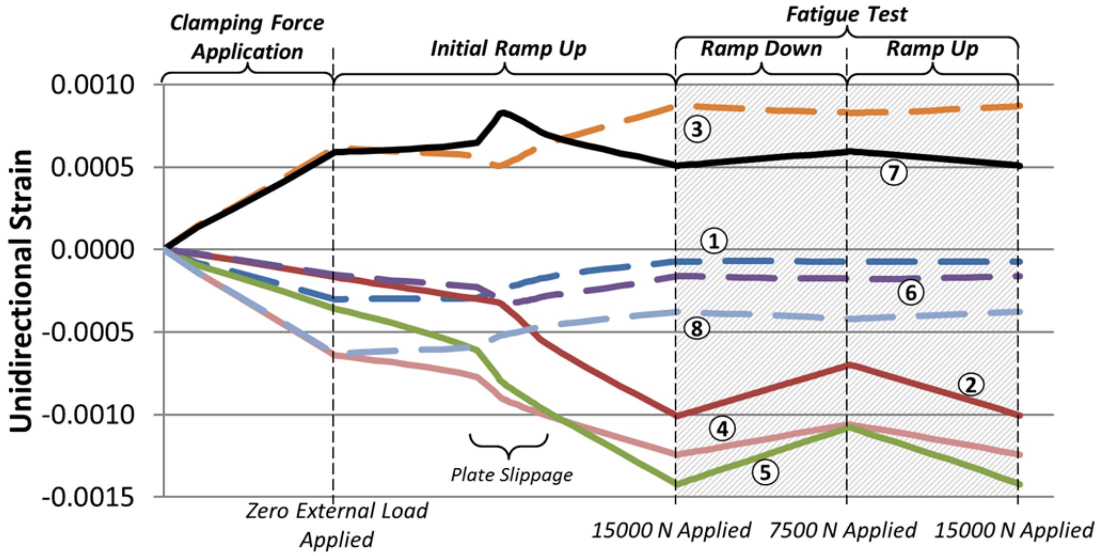

Fig.5. Strain during the several phases of the test in the eight considered locations.

The proposed algorithm to detect the loss of clamping force during fatigue tests is divided into six steps:

1. The algorithm recognises the load cycles in the data, identifying the position and values of the maximum and minimum loads for each cycle through the use of the two load thresholds. The maximum load is defined as the maximum value found above the top threshold and the minimum load as the minimum load found below the bottom threshold. When the load passes, first, through the top and, then, through the bottom threshold, the recorded maximum load is saved and a new collection is started. The opposite concept is used to identify the minimum load.
2. The entire data collection is divided into half-cycle sets delimited by the identified maximum and minimum loads. Each half-cycle set represents either the ramp up or the ramp down of a load cycles.
3. For every half-cycle set, a linear regression is run using the method of the least squares to obtain the best fit of the strain vs. external load data. The equation of the best fit line is then used to extrapolate the value of the strain related to a zero external load (Fig.6), which is the strain caused only by the clamping force. A decrease in this strain thus indicates that the bolts are losing clamping force. For every cycle two values of zero-load strain are produced from the code: the first is related to the extrapolation from the ramp up set of the cycle and the second is related to the ramp down set. The difference between these values is a good indicator to assess at every moment of the test the amount of non-linearity in the readings and therefore the validity of applying the superposition principle.
4. To calibrate the method, it is necessary to record and use as references the strain gauges readings after the joint failure (strain corresponding to zero clamping force). Another suitable way to calibrate the method, having a more quantitative evaluation but using a more complicated set-up, is to apply the strain gauges before the bolt tightening and record the strain before and after the clamping force is applied.
5. A Clamping Force Index (CFI) is calculated for each cycle, both for the ramp up and the ramp down, for each bolt. The Clamping Force Index for the cycle i is defined as:

$$CFI_i = \frac{\varepsilon_i - \varepsilon_{fin}}{|\varepsilon_{ini} - \varepsilon_{fin}|};$$

where ε_i is the extrapolated strain for the i-th cycle (either for the ramp up or the ramp down), ε_{ini} the extrapolated strain found at the first cycle of the test and ε_{fin} is the strain used as reference for a zero load applied.

6. A graph for each bolt is produced showing the values of the Clamping Force Indexes (both from the ramp up and the ramp down sets) vs. the cycles.

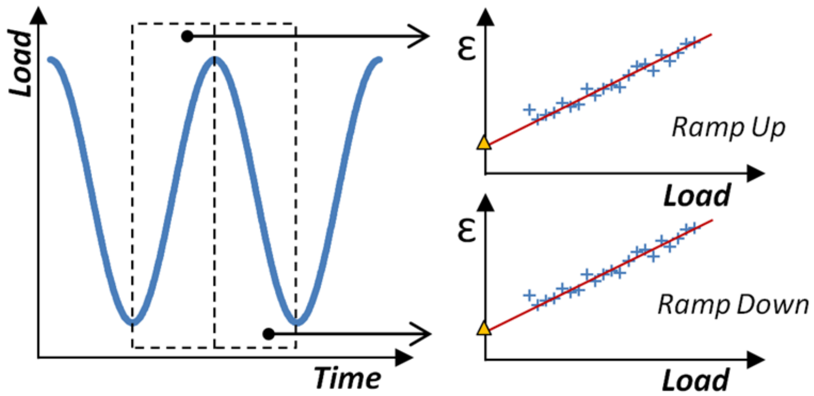

Fig.6. Extrapolation of the strain associated to a zero external load applied.

This method can be applied to every type of cyclic load and without the need of knowing the R ratio, the maximum and minimum loads or the load frequency. The shape of the load-time graph does not have to be a sinusoid but can be any periodic function. Maximum and minimum loads and frequencies can be changed throughout the test, making the method suitable to be used in fatigue tests with complex load spectra.

3 Preliminary results

The presented method has been tested on composite bolted joints under single lap shear fatigue tests. The R ratio used was 0.1 and the frequency 7 Hz. The joint final failure was characterised by fastener failure with cracks at the head root of both bolts and by very limited damage on the composite plates.

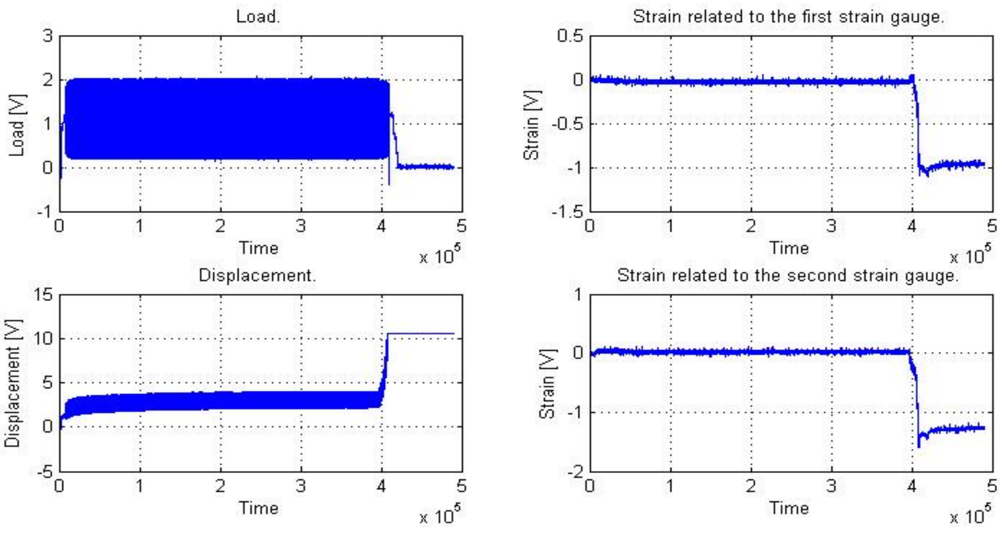

Fig.7. Raw data recorded during the fatigue test: load and displacement from the machine sensors and two strain readings from the strain gauges located next to the nuts.

Fig.7 shows the raw data obtained from one of these fatigue tests:

- load, which oscillates between a minimum and a maximum value until the joint final failure;
- displacement, which also oscillates following the load and increases slowly throughout the test until a sudden increase, associated with a fast damage propagation (displacement readings are not required for the proposed method);
- strain associated with the first bolt, which oscillates with an almost constant form for most of the test with a strong decrease close to the end of the test;
- strain associated with the second bolt, similar to the previous one.

After having processed the data using the proposed algorithm, it has been possible to obtain the graph of the Clamping Force Index of the two bolts during the fatigue test. Fig.8 shows that the entire test lasted for 10,046 cycles, with the clamping forces of the two bolts having almost constant values for most of the test. From about 300 cycles before the final joint failure, the clamping forces dropped and kept decreasing until final failure, caused by fastener failure.

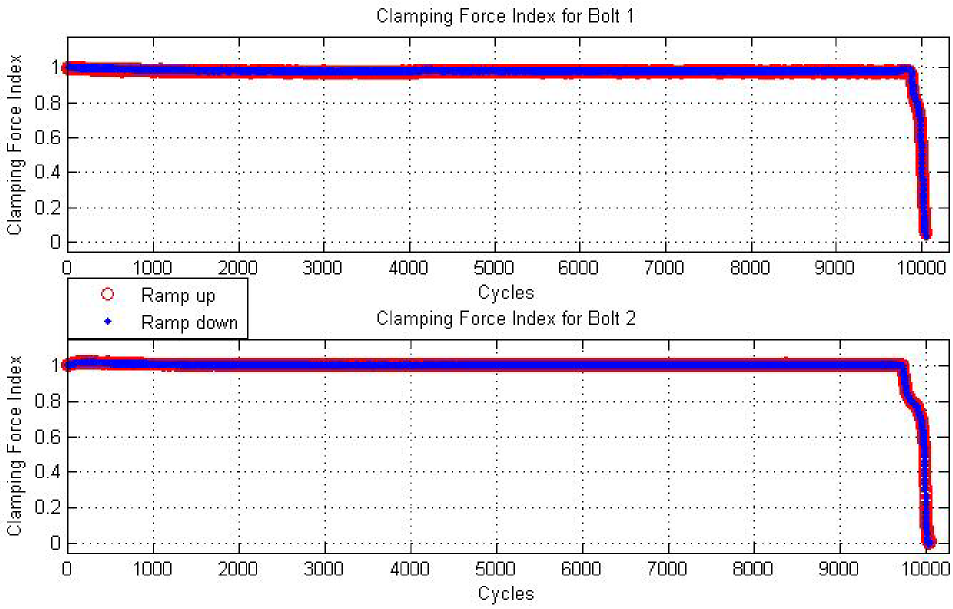

Fig.8. Result of the method - Clamping Force Index in the two bolts throughout the cycles.

Regarding the validity of the superposition principle assumed, in Fig.8 it is possible to see, in different colours and symbols, the values of the Clamping Force Indexes obtained analysing the data of the ramp up and ramp down of each cycle. The two sets of values are very similar, especially in the first part of the test. After the clamping force drops, the difference between the two sets is at the highest of the entire test; this is likely caused by the damage developed in the bolts or in the plates, which add non-linearity to the strain response.

4 Discussion

Fig.8 shows that the values of the Clamping Force Index are almost constant for most of the test. The drops in the CFI near the end of the test highlight a relatively quick damage propagation. The damage initiation stage seems to last for a much longer fraction of the joint fatigue life than the damage propagation stage. This fatigue behaviour allows the joint to have a reliable mechanical response for most of its fatigue life, with an unchanged bolt clamping force and a constant joint stiffness, but also leads to a fast damage development which could be difficult to detect before the final failure.

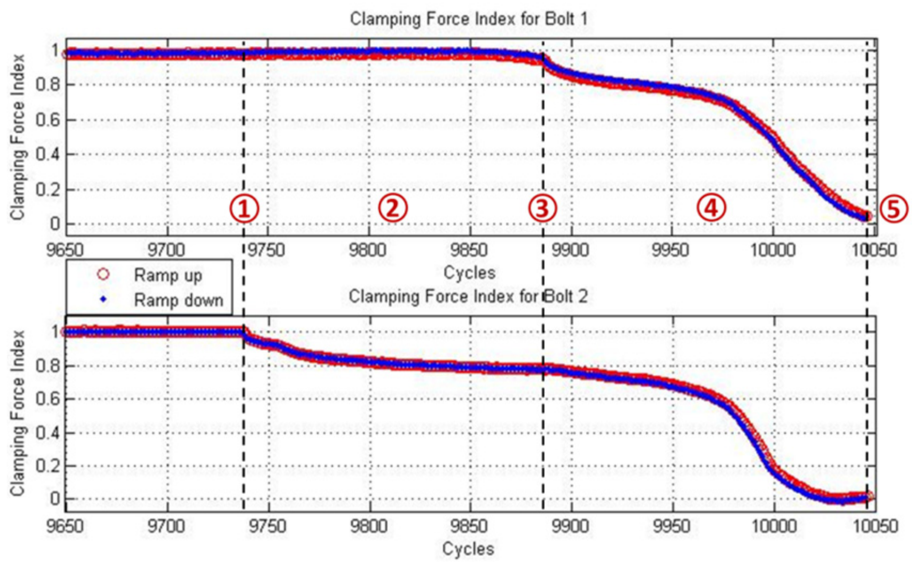

Fig.9. Detail of the failure process of the two bolts – (1) 2nd bolt crack initiation, (2) transfer of load and crack propagation deceleration, (3) 1st bolt crack initiation and increased velocity of the crack in the 2nd bolt, (4) crack propagation velocity of both bolts increased and fast but stable fatigue crack propagation, (5) final failure.

In Fig.9 a detail of the Clamping Force Index vs. cycles graph during the last part of the test is shown. It is possible to identify a sequence of events leading to the joint final failure:

1. Sudden drop of CFI in the second bolt. This is likely to be correlated to a crack initiation in the bolt head root (location of the final failure);
2. Slightly increased reading of CFI in the first bolt and slower loss of CFI and reduced damage propagation rate in the second bolt. The damage in the second bolt leads to a change in the distribution of load between the two bolts: part of the load, which was carried by the second bolt, now more compliant because of the damage, is transferred to the first bolt. The load transfer causes an apparent increased reading of the CFI of the first bolt. The fact that this increases so slightly indicates that the method proposed is effective in screening out the effect of the external cyclic load. The decreased load carried by the second bolt causes the damage propagation rate to strongly decrease. The global effect is the transfer of load between the bolts with the protection of the damaged bolt by the undamaged one.
3. Sudden drop of CFI in the first bolt. This is likely due to a crack initiation in the head root of the first bolt. This causes a more even redistribution of the load carried out by the two bolts and an increment of the crack propagation rate in the second bolt. This is confirmed by the CFI readings: at the instant when the crack initiates in the first bolt, it is possible to observe a change of the shape in the CFI vs. cycles curve of the second bolt.
4. Both fasteners are failing and the crack propagation rates increase progressively. The shapes of the curves in the two bolts are initially different but, with the developing of the damage and with additional load transfers, become rapidly similar. The fatigue crack propagation in the last phase is fast but stable; since in the graphs every point represents the reading of an entire cycle, it is possible to notice that the last phase of the failure process is characterised with a high but almost constant crack propagation rate. This phase lasted about 150 cycles in the presented test.
5. Final failure of the joint with fully propagated cracks in both bolt heads. The last point in both graphs represents the CFI for the last load cycle that the specimen has been able to complete before final failure. It is possible to note that in the Bolt 2 the CFI has already

reached a value around zero before the joint final failure. Instead Bolt 1 still retains a little amount of clamping force which is lost statically during the ramp up of the uncompleted last cycle.

5 Conclusions

This paper has presented an effective method to monitor the loss of clamping force and detect crack initiation and propagation in the fasteners of composite bolted joints during lap shear fatigue tests.

The method requires the load readings from the machine load cell, the data from a strain gauge located close to each bolt and an algorithm which has been developed to post-process the data. The method assumes the linearity of the strain with the clamping force and with the external load, and the superposition of the two effects. The correct location and orientation of the strain gauges has been chosen using a detailed FE model. The algorithm developed to post process the results divides the raw data in half-cycle sets and runs an extrapolation on each of them to find the strain correlated with a zero external applied load, which is the strain related only to the clamping force.

The test results show an almost constant value of the extrapolated strain (i.e. therefore of the clamping force) for most of the fatigue test, followed by a relatively sudden decrease in the strain value due to crack propagation in the bolts. The cycles in which the cracks initiated in each bolt were clearly identified by the algorithm. The results also show the interaction between the bolts during the failure process. When the first bolt starts to fail, part of the load that it carries is transferred to the undamaged bolt, decreasing the rate of change of strain with cycles of the former and reducing the crack propagation rate of this. During the last cycles, the fatigue cracks propagate in a fast but stable way until final failure of the joint.

The proposed method could be used with any periodic load cycle and with different maximum loads, R ratios and load frequencies during the test, making it suitable to be applied to fatigue tests with complex load spectra.

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