HOLLOW FIBER-REINFORCED STRUCTURAL CORES FOR COMPLEX PART MANUFACTURING

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Keywords: Aeronautics, carbon-fiber, composite, novel manufacturing process, CFRP core, modified co-curing, T-joint, structural testing

ABSTRACT

The current manufacturing technologies employed for hollow composite structures come with design limitations, particularly in terms of limited integration potential. Differential designs consisting of multiple parts and subsequent assembly are constrained, affecting lightweight construction and load transfer due to the reliance on joints. This paper introduces a patented concept of structural carbon-fiber reinforced plastic (CFRP) cores, aiming to overcome these restrictions and enable integral and complex designs. The CFRP cores are initially manufactured and partially cured using Resin Transfer Molding (RTM). They are then integrated into a dry textile-based preform, serving as support structures during another RTM process. The key aspect of this process is the utilization of modified co-curing, which combines partially cured components with uncured ones, resulting in optimized bonding capabilities. The primary application of this patent lies in the use of CFRP cores as structural load-bearing elements within the component. The effectiveness of this novel manufacturing approach, employing structural CFRP cores, was successfully demonstrated through its application to an exemplary aeronautical structure and validated by structural testing.

1 INTRODUCTION

The manufacturing of hollow CFRP components (e.g. composite flaps) in a RTM-process normally requires metallic cores to stabilize the walls during resin injection. This often limits the freedom in design for those components. If the part is curved, conical shaped or has some undercuts it can become very difficult or sometimes impossible to remove the metallic cores after curing. In this case, normally water-soluble cores or so-called “lost cores” are used. Washable cores are expensive and difficult in handling. Lost cores, e.g. foam cores, normally increase component dead weight without contributing to the structural stiffness and strength. To realize a lightweight structure and to overcome these disadvantages CFRP structural cores were developed and patented (DE102015107281B4) by the Leibniz-Institut für Verbundwerkstoffe. The CFRP structural cores are hollow-shaped blocks with a high degree of design freedom which stabilize the surrounding material during manufacturing in an RTM process. The structural cores can replace metallic cores and enable the production of even more complex components in an RTM process. The walls of the structural cores become a part of the manufactured component itself without generating any additional weight and they do not have to be removed after curing. This concept is shown in Figure 1. The challenges when using structural cores are on one hand the stability of the core during the RTM process. On the other hand, the connection between the walls of the structural core and the surrounding material represents a decisive criterion for the mechanical performance of the component. To achieve an optimized connection a so-called modified co-curing process was developed to connect pre-cured structural cores with non-cured surrounding material in one process. The process to manufacture components with the patented concept of structural cores in a modified co-curing process is presented in this paper.

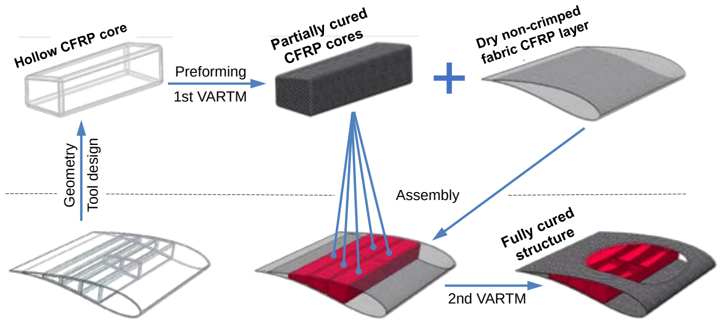

Figure 1: Implementation of structural CFRP cores in aircraft airfoils (e.g. flaps): from geometry derivation to core fabrication and structural assembly with multiple CFRP cores; achieving a final fully cured sectional structure with added stiffening elements from core walls.

2 MODIFIED CO-CURING PROCESS

Depending on the degree of cure of both partners, a distinction is made between co-bonding and co-curing when bonding them in one step. Co-curing means the joining of non-cured components in one step using chemical crosslinking as coupling mechanism. Co-bonding, on the other hand, refers to the joining of a fully cured structure with a non-cured structure. An adhesive film can be used in the connection zone to improve the bonding strength. In the modified co-curing process discussed in this work, partially cured structures are fully cured together with non-cured components in the subsequent step. The quality of the bond directly depends on the degree of cure of both components: the lower the degree of cure, the stronger the bond but also a sufficient stability of the core during the following handling and RTM-process is necessary.

To measure the degree of cure α the link to the glass transition temperature Tg was investigated by using a DiBenedetto model, which is given by (1):

$$Tg = Tg0 + \frac{(Tg\infty - Tgo)\,\lambda\alpha}{1-(1-\lambda)\alpha} \tag{1}$$

with $Tg0$ = Tg of the non-cured resin; $Tg\infty$ = Tg of the fully cured resin and λ, correction factor. For this model, the correction factor λ was assessed with data from DSC-measurements of the RTM6 resin (λ = 0.473) [1]. By measuring Tg the equation can be transposed to find the unknown α.

3 MATERIALS AND METHODS

For core and demonstrator manufacturing a non-crimp fabric (NCF) using carbon HTS40 fibers in combination with Hexcel RTM6 resin (details in Table 1) was used. *Spunfab*® binder fleece (6 g/m²), allowing for preforming and layer attachment by ironing was covered on both surfaces.

Table 1 Materials, semi-finished product and layups used for manufacturing

Resin	Hexcel RTM 6, 2 Component system
Fiber	Carbon HTS40 in 12K filaments
Fabric (MCB shell)	Biaxial NCF (Areal weight 330 g/m²)
Layup core (t = 2.2 mm)	$(+45/-45/90/0/-45/+45)_s$
Layup cover shell (t = 1.1 mm)	+45/-45/90/0/-45/+45
Layup referential spar (t = 2.2 mm)	$(+45/-45/90/0/-45/+45)_s$

For the RTM 6 resin, the cure cycle in the material datasheet refers to an injection at 120 °C followed by a temperature increase to 180 °C for 90 minutes [2]. Resin temperature for injection should be 80 to 90 °C. An additional cure step is added in between at 140 °C for 90 minutes to reach a degree of cure of approx. 65 % suitable for modified co-curing later on [3].

The manufacturing process is based on the reference structure known as the multi-cell box (MCB), as depicted in Figure 1. The tooling approach employed is similar to the one used for the multispar flap, which is described in [4]. In the MCB, the hollow sections are formed using solid metallic mandrels. This demonstrator enable the extraction of T-joints for subsequent structural testing, such as T-pull tests.

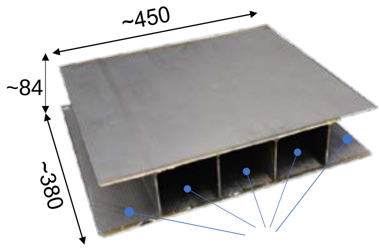

Figure 2: Reference structure – MCB demonstrator.

In the integrated core (IC) design – manufactured with CFRP-cores - the three inner mandrels are replaced. The dimensions of the CFRP cores are derived from the outer shape of the metallic mandrels. To manufacture a hollow CFRP core, a bladder manufacturing process is selected, where the bladder's shape corresponds to the inner dimensions of the CFRP core. Preforming is conducted on the bladder, necessitating its stabilization. The subsequent section provides a detailed discussion of the steps involved in manufacturing an MCB in the IC design.

4 MANUFACTURING OF STRUCTURAL CFRP CORES

A bladder process has been selected as an optimal method for manufacturing hollow structural CFRP cores (Figure 3). This process allows for easy removal of the bladder after component completion without adding any extra weight. Given the strict tolerances required for subsequent manufacturing steps and the closed shape of the core, it is crucial to preform and stabilize the bladder. The bladders are created using a two-component silicone mixture (*ZA50LT* from *Zhermack*), evenly distributed within a mold consisting of two separate halves. To ensure uniform distribution, the sealed mold is manually rotated until the gel time is reached, typically after one hour. Although silicone was chosen for bladder production in this research project, it can potentially cause contamination during the manufacturing process. Therefore, when the process is industrialized, a safer alternative material should be considered. The bladder features a nozzle that aids in stabilizing the pre-cured structural core during the subsequent part manufacturing stage using pressurized air. [7]

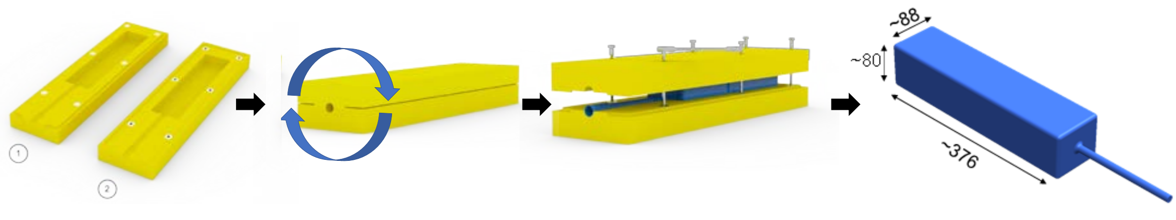

Figure 3: Bladder manufacturing process from left to right: Empty mold which will be filled with 2K silicone, closed mold, followed by rotational molding, mold opening and removal of bladder

After manufacturing of the bladder, the bladder is placed inside the mold again, filled with sand and stabilized by several vibration processes. By using an inline filter connected to a vacuum pump, the bladder is compressed, causing the sand to interlock and leaving a stabilized bladder. The stabilized bladder is then used to manufacture the preform of the structural CFRP core by hand lay-up (Figure 4). Six biaxial layers are placed on the stabilized core with an alternating fiber direction (see Table 1). To reach a sufficient laminate strength the shape of the biaxial layers are different to ensure sufficient overlapping length of the layers.

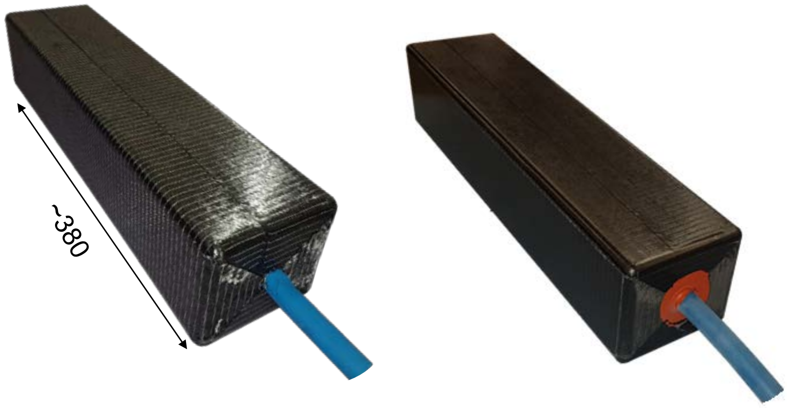

Figure 4: CFRP preform of structural core and partially cured structural core with sealing

To achieve a MCB manufactured in a modified co-curing process the following process steps were carried out for the CFRP cores. First the sand was removed, then the preform was placed in a closed tool and was stabilized with pressurized air during the following curing process (Vacuum assisted resin transfer molding - VARTM) until a predefined degree of cure (Figure 5).

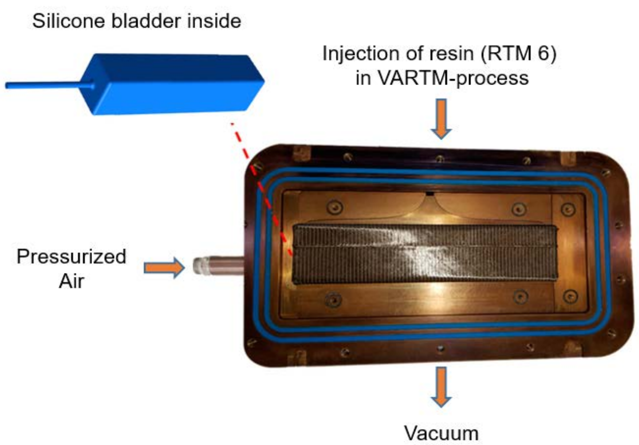

Figure 5: CFRP preform in core tool (opened) during manufacturing of pre-cured structural core

The CFRP core LCM process underwent various trials, with particular attention given to dry spots at the edges following RTM processing, which were visually detectable. Potential causes of these issues include leakage, problematic resin flow, or gas expansion from the resin under high temperatures. Flow or impregnation problems were deemed unlikely due to their successful application in the reference MCB, which was more complex. Addressing leakage involved sealing the transition from bladder to preform. To minimize gas expansion during injection, the resin was degassed twice at 90 °C and 110 °C. However, these changes did not improve impregnation. Consequently, the problems were attributed to either preform quality or influenced by process parameters. Since the preform's dimensions and edge geometry were fixed, process parameter modifications were pursued by varying injection and internal bladder pressure, as suggested in literature [5],[6]. This approach reduced the occurrence of dry spots at the edges. The suitable process involved an initial injection pressure exceeding the internal pressure for 60 seconds at 0.5 bar. Both pressures increased incrementally until reaching limits of 4 and 5 bar for injection and internal pressure, respectively. It should be noted that preform quality may also play a role, influenced by manufacturing experience. Figure 4 illustrates a partially cured core after completion. To achieve the desired Degree of Cure (DoC) α, a previously established curing cycle was utilized, involving a restricted temperature of 140 °C for 90 minutes in the VARTM process [3]. Considering the higher thermal inertia of the CFRP core tooling compared to coupon-level specimen manufacturing, the tooling was removed from the oven after reaching the desired curing time and cooled using convection through ventilating air. DoC analysis involved extracting resin specimens from different positions in the mold and measuring the glass transition temperature via differential scanning calorimetry (DSC).

5 MANUFACTURING OF COMPONENTS BY MEANS OF STRUCTURAL CFRP CORES

In the subsequent VARTM process, the MCB is assembled, consisting of three adjacent CFRP cores with gusset fillers and dry shell layers that follow the same layup as the reference. To enable pressurization of the CFRP cores, modifications are made to the tooling used in the mandrel-based process. Pressurization is chosen as a conservative approach to validate the modified co-curing concept (MCC) as a proof of concept. Consequently, the front mandrel carrier is separated to accommodate the bladder tubes, and additional nozzles are incorporated into the frame. These modifications are depicted in Figure 6 a), showcasing all the necessary components.

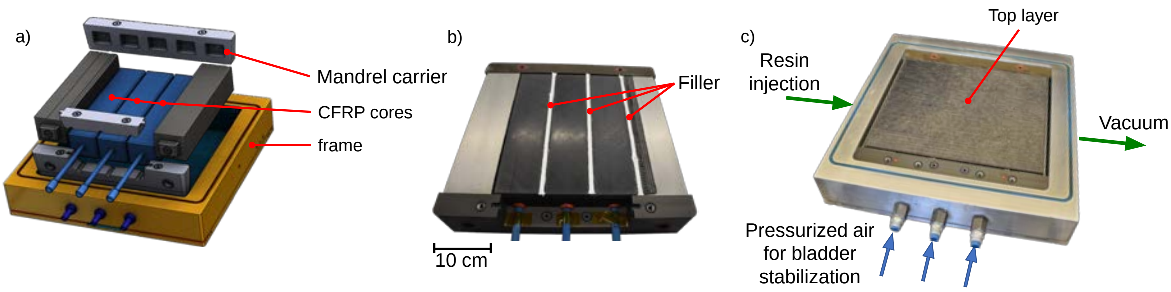

Figure 6: MCB manufacturing in the modified co-curing process – Adapted tooling a), Assembly of structural cores, metallic mandrels and gusset filler b), Applying top layer and concept of RTM-process c)

Figure 6 b) illustrates the assembly of the three neighboring CFRP cores with added gusset fillers in the mandrel carrier. Once the mandrel carrier is inserted into the frame, the setup is finalized by adding top and bottom layers and closing the tooling with its cover. Subsequently, the VARTM injection process begins (Figure 6 c)). Unlike the first VARTM cycle, the bladders are pressurized at constant pressure of 4.5 bar, while the resin is injected at 3 bar. The same curing cycle as employed for the reference MCB is utilized, resulting in a fully cured component.

6 RESULTS AND DISCUSSION

6.1 MCB MANUFACTURING

Figure 7 displays a final MCB (Multi-Cell Box) that has undergone the modified co-curing process, resulting in the integration of CFRP (Carbon Fiber Reinforced Polymer) cores. In the accompanying cut view on the right, a detailed representation of a wall composed of two CFRP cores is provided.

Figure 7: MCB demonstrator with integrated structural cores (left) and cut view with removed bladders (right)

The exemplary fiber alignment within the MCB exhibits a high level of quality without any noticeable deviations. However, some minor imperfections in the form of resin agglomerations can be observed in certain internal sections, which are likely a result of the CFRP core injection process. Thermographic non-destructive testing (NDT) was conducted on the MCB utilized for testing purposes, revealing no interlaminar defects. In total, three MCBs with CFRP cores were manufactured, with two of them utilized specifically for structural testing objectives.

6.2 STRUCTURAL TESTING

T-joint testing is conducted using four specimens: referential (R) and integrated CFRP core (IC) configurations. The peak force in T-pull tests indicates structural integrity. Differences in laminate thickness affect bending stiffness and failure behavior. Mode I loading at the interface diminishes laminate differences, allowing R and IC designs to be compared. Digital image correlation highlights stress concentrations and failure progression. Figure 8 illustrates detailed failure examination of the R and IC configuration.

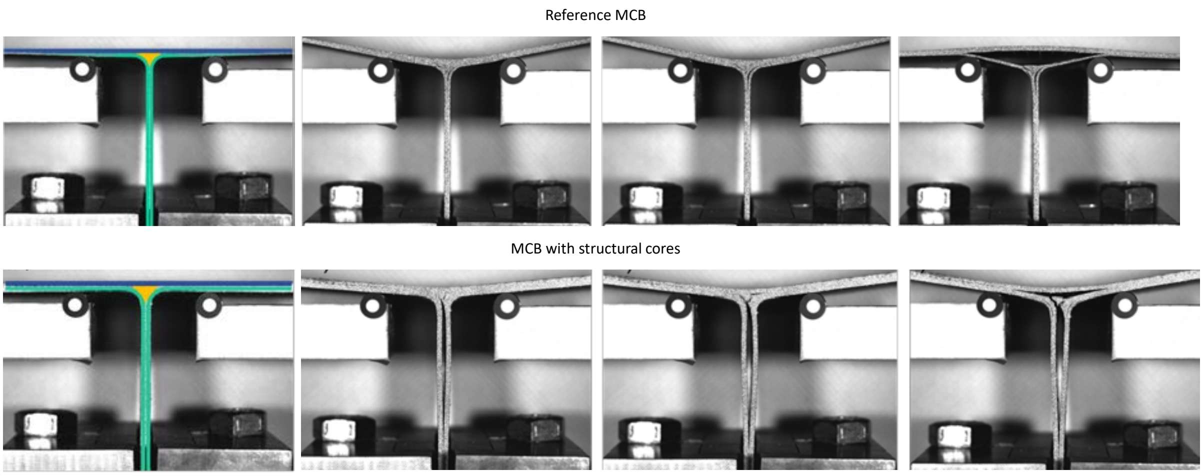

Figure 8: Failure occurrence and progression in T-pull test for reference configuration (R design, upper row) and MCB manufactured with structural cores (IC design, lower row)

For the R configuration initial peak stress in the radial section leads to crack propagation across, culminating in sudden delamination. Final failure involves complete spar detachment from the top layer. The force-displacement plots (Figure 9) for the four R specimens share similar patterns. Crack initiation (~2.5 to 3.1 kN) leads to a decreasing slope, followed by sudden propagation and drop. Subsequent increase generates slightly higher force peaks, repeating until the final failure with the highest peak. Crack initiation for IC specimens occurs between the CFRP core and radial section, propagating within the CFRP core interface. Force drops transpire when the crack progresses into the radial section and subsequently the interface with the top layer. While crack propagation occurs, the consistent laminate thickness and absence of a runout prevent final failure. However, the core-core interface experiences complete failure without affecting the force-displacement plot. This interface becomes more critical in bending tests, as it transmits shear stresses. The configurations exhibit distinct failure behavior.

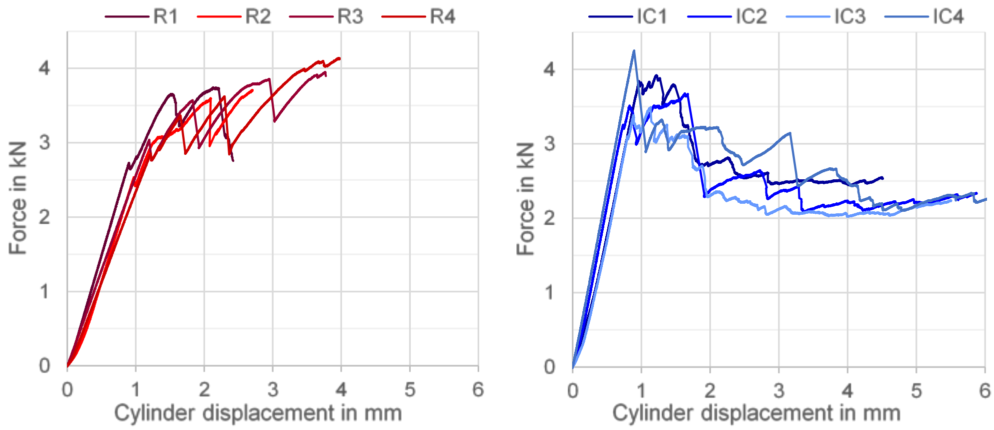

Figure 9: Force-displacement plots of the referential (R) and integrated core (IC) configuration

Comparing the overall performance of R and IC T-joints, mean peak forces only slightly differ. Detailed measured values are depicted in [7]. However, considering the combination of partially cured CFRP cores with the uncured top layer manufactured through modified co-curing, the difference is relatively small compared to the referential co-curing structure. The IC T-joint test demonstrates distinct failure behavior evident in Figure 9 (right) force-displacement plots. Compared to the referential tests, IC specimens exhibit notable differences: a steeper initial increase, an early peak force, and no final failure despite greater displacement. Early peaks reach the highest force. The force-displacement plot degrades consistently after primary failure, interrupted by minor stress peaks during crack propagation between CFRP cores and the top layer.

The IC design displays direct failure with crack initiation at the weak core-core interface. Although this failure is not critical for the test setup as load transfer remains possible, it poses concerns for bending applications. One proposed solution is adding an uncured layer between the cores to enhance interface strength. Conversely, the consistent and runout-free layup of the IC configuration yields superior overall performance, avoiding complete debonding of the cores from the shell layer. DIC strain computation aids in investigating initial failure.

7 SUMMARY AND OUTLOOK

This paper presents a patented solution for structural load-bearing CFRP cores in aeronautical applications, along with a manufacturing process concept supported by a demonstrator structure. The CFRP cores are manufactured using a bladder process, where preforming of the non-crimp fabric involves stabilizing the bladders with sand filling and vacuum application. After preforming, the sand is removed, and the preform is inserted into the respective RTM tooling. Modified co-curing is crucial for achieving stability and load-bearing capabilities of the CFRP cores during handling and further processing, while ensuring bonding with other components. The desired level of partial cure is achieved through a defined cure cycle, resulting in CFRP cores with degrees of cure ranging from 63% to 70% [7], close to the lower process boundary of 59% for optimized bonding strength [3]. Dry sections on the surface of CFRP cores were resolved by adjusting the injection process, with stepwise increase of injection and internal pressures, momentarily exceeding the internal pressure. Challenges in the manufacturing process include precise preforming on the stabilized bladder and achieving consistent partial cure throughout the cores, despite variations influenced by manufacturing conditions.

The demonstrator structure involves a multi-cell box where three steel mandrels are replaced with hollow CFRP cores. Tooling modifications are made to accommodate the bladders as a conservative measure in the manufacturing step. Both referential and integrated core configurations of the MCB are realized. Structural testing of T-joints extracted from the respective MCBs compares the two configurations, demonstrating structural integrity and similar peak forces in the integrated core process. However, failure behavior differs primarily due to variations in laminate thickness to the shell and the weak core-core interface. While the overall performance is superior, improvements are required for the core-core interface, such as the use of an uncured layer in between.

Future steps include developing CFRP cores with asymmetric layups to enable lighter designs, exploring design variations using additive manufactured hulls instead of bladders to increase design flexibility and reduce costs, and eliminating the need for bladders in the second integrative manufacturing step by sealing the CFRP cores for simplified processing. The advantages of using CFRP cores, such as curvatures, thickness deviations, undercuts are to be realized in follow-up projects.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding in scope of the project „Next-Move – Design & Assembly Concepts of Next Generation Moveables” by the Federal Ministry of Economic Affairs and Climate Action on the basis of a decision by the German Bundestag (funding reference 20W1512D).

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