FIBER ARCHITECTURE BASED DESIGN OF DUCTILE COMPOSITE REBAR FOR CONCRETE STRUCTURES

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SUMMARY: Fiber Reinforced Plastic (FRP) has been identified as an attractive candidate material for civil infrastructure applications because of its light weight, high strength, non-corrosive and non-magnetic characteristics. In spite of these attractive features, the adaptation of FRP to civil infrastructure applications has been slow especially in concrete reinforcements. This can be attributed to the lack of ductility of the state-of-the-art FRPs which have linear elastic tensile stress-strain behavior up to ultimate load and they fail in a brittle mode. Thus the flexural response of these FRP bars in reinforced concrete beams and slabs exhibit little ductility and therefore makes it impossible to design such members based on ultimate strength principles. There is a need for a FRP rebar system which has a steel-like stress-strain behavior. The aim of this paper is to demonstrate a design concept for a ductile composite rebar utilizing low cost textile preforming technology supported by an integrated fiber architecture based designing methodology.

KEYWORDS: braid fiber architecture, FRP, hybrid, ductile, ribs, reinforced concrete, structural hierarchy, braiding, pultrusion

INTRODUCTION

Structural repair of deteriorated reinforced concrete (R/C) and pre-stressed (P/C) concrete structures is rapidly becoming a more economical option for constructed facilities in the United States. Corrosion of steel reinforcement, which is a primary factor in reduced durability of concrete structures especially in the more severe climates where deicing compounds are used, has prompted the need to seek steel substitutes. In general FRP systems, which usually consist of glass, aramid, or carbon fibers in a polymer matrix, have high strength, low modulus of elasticity and very low ultimate tensile strains as compared to steel as illustrated in Fig. 1. showing the brittle failure behavior of typical GFRP, AFRP, and CFRP systems. The lack of ductility is undesirable for civil engineering structures. As a result it precludes our exploitation of the advantages such as low weight, corrosion resistance, and non-magnetic properties provided by the FRP reinforcement in new and repaired concrete structures.

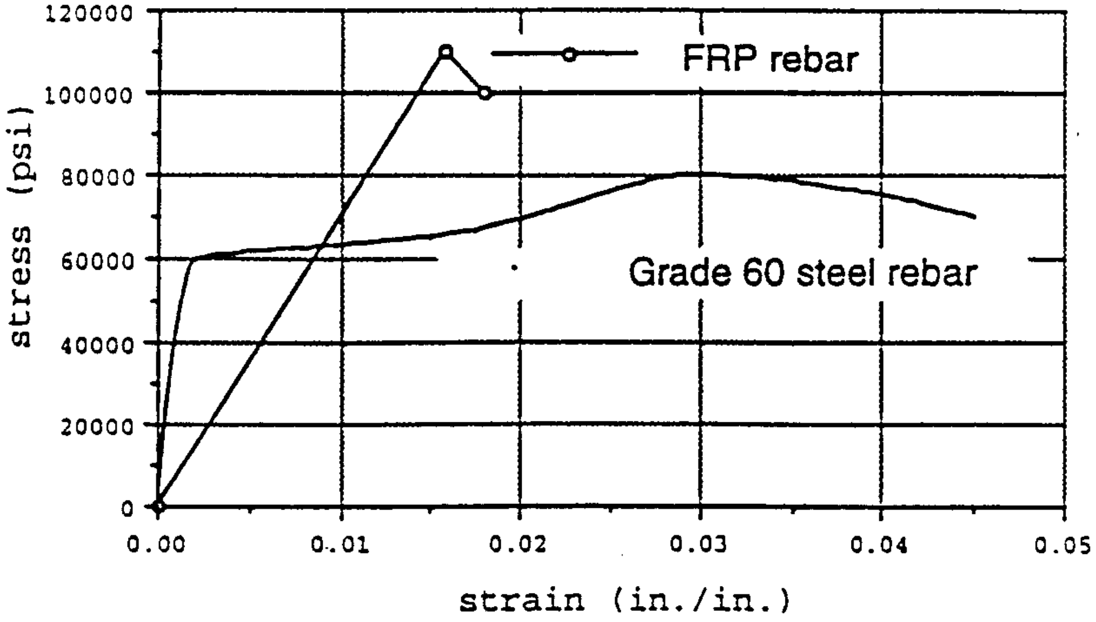

Fig. 1 Comparison of Stress-Strain Properties of FRP Bars with Steel

There is a need for a low cost composite system which has a sufficient level of stiffness and can fail in a ductile or "pseudo-ductile" manner. To facilitate the adaptation of the new design concept and material systems to infrastructure applications, it would be desirable to establish an engineering design base which takes material processing parameters and civil engineering parameters into consideration. It is desirable to develop a composite rebar system which has stress-strain behavior similar to that of the steel reinforcement (Fig. 1).

DESIGN CONCEPT

Taking advantage of the design flexibility and the wide availability of manufacturing capacity in the industry, braided structures will be employed as the primary fiber architecture for the construction of the proposed hybrid FRP rebar system. The technology of braiding , as detailed by Ko [3,4] is a well established technology which intertwines three or more strands of yarns to form a tubular structure with various combinations of linear or twisted core materials. By judicious selection of fiber materials and fiber architecture for the braid sleeve and the core structure, the load-deformation behavior of the braided fibrous assembly can be tailored. As illustrated in Fig. 2, the sleeve structure may be a tough aramid (e.g. Kevlar) fibrous structure whereas the core structure would be high modulus carbon fibers to provide the initial resistance to deformation. The rib effect, as commonly incorporated in steel rebar to increase bond strength between the rebar and concrete, can also be introduced to the sleeve structure during the braiding process. By proper combination of the braided fibrous assembly with a protective resin matrix system to form a composite material system, the stress transfer from the rebar structure to the fibers can be controlled. The end product of this hybridization of material systems and fiber architecture is a composite rebar which has high initial resistance to tensile deformation followed by a graceful failure process manifested by a gradual reduction in the slope of the stress strain curve before reaching a high level of ultimate strain as shown in Fig. 3. Note from Fig. 3 the high initial modulus obtained for the newly developed 5 mm. hybrid FRP bar which has essentially bi-linear stress-strain characteristics. A reduction in the stress fluctuations shown in Fig. 3 will be achieved by modifications to the braid architecture.

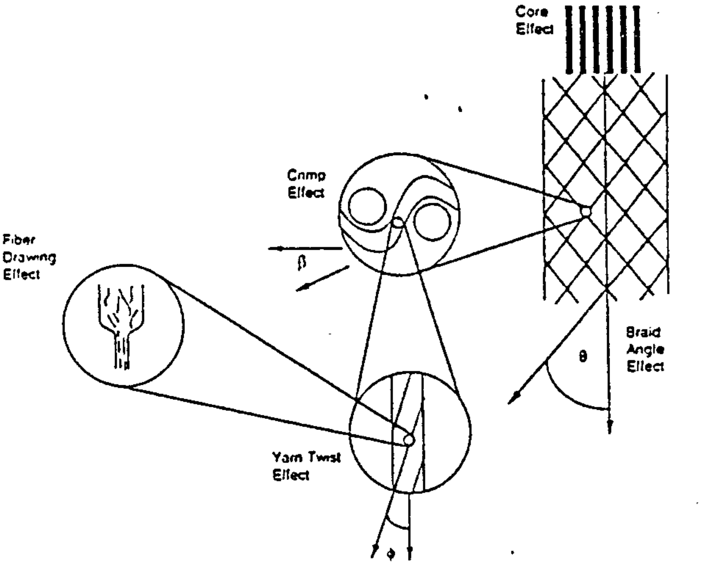

Fig. 2 Structural Hierarchy of the Braided Rebar

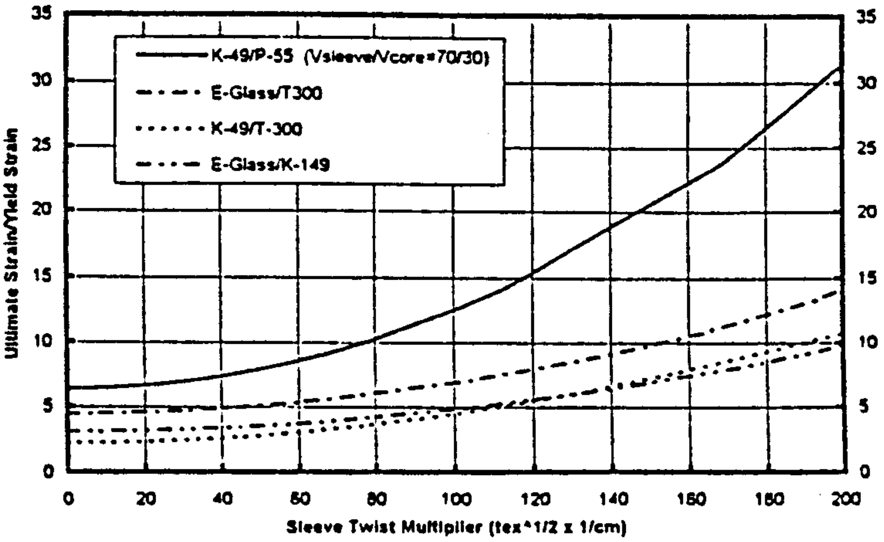

Fig. 3   Stress-Strain Characteristics of Braided Composites.

FIBER ARCHITECTURE BASED DESIGN

The Fabric Geometry Model

The development of the composite rebar system is based on an understanding of the structural hierarchy of the braided reinforcement assembly established at Drexel University over the past decade. This fundamental understanding revealed that the translation of the fiber material properties and effect of braiding process parameters can be related to the mechanistic response of the composite rebar system through the geometric relationships between the various structural levels. The result is a Fabric Geometry Model (FGM) developed by Ko et al

[5] for braided composite systems linking fiber and matrix properties, fiber architecture and processing parameters to the engineering material coefficients required for finite element stress analysis. Based on a modified laminate theory, the FGM quantifies the fiber architecture of the braided structure in terms of a unit cell. A stiffness matrix for each yarn system, $[C_i]$, is then obtained by transforming the stiffness matrix for a comparable unidirectional composite rod , $[C]$,through the following equation:

$$[C_i] = [T_{\Sigma,i}]^T [C][T_{\Sigma,i}] \tag{1}$$

where $[T_{\Sigma,i}]$ is a transformation matrix containing the directional cosine of each component yarn system. The total stiffness matrix for the braided composite structure can be obtained by the volume averaging of $[C_i]$. Through a piecewise linear approximation, the nonlinear stress-strain relationship resulting from matrix material, interfacial debonding and fiber distortion can be accounted for by an incremental strain analysis. Failure prediction can be accomplished finally by invoking the maximum strain energy criterion.

Hybrid Effect

The combination of different types of fiber and fiber architecture produces a hybrid effect which gives rise to the "pseudo ductile" behavior of the composite. In our study, a low elongation high modulus component - the carbon core fiber bundle, is surrounded by a higher elongation component - the Kevlar braided sleeve. The selection of the relative proportion and the nature of the combination of the types of fiber twist geometry and braid architecture were guided by an analysis of the hybrid effect as shown in Fig. 4.

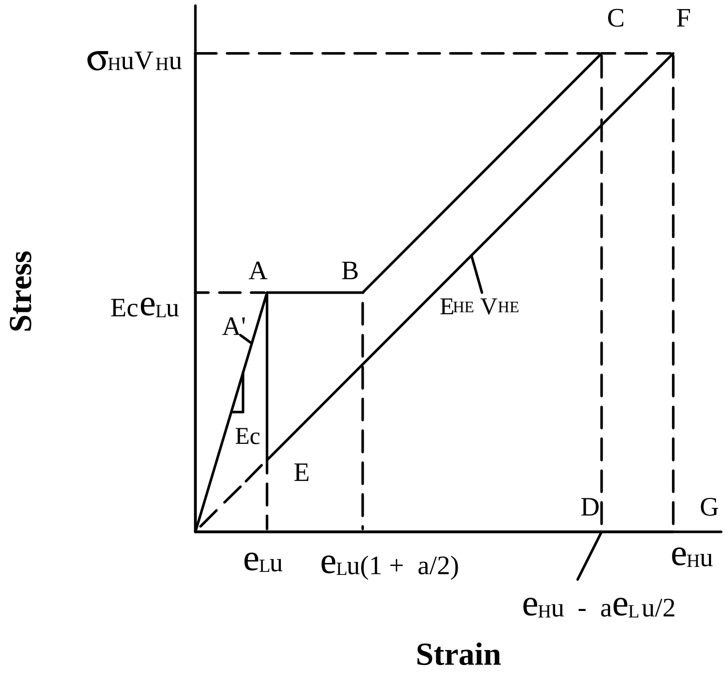

Fig. 4 Hybrid Composite Consisting of High and Low Elongation Components.

As demonstrated by Averston and Kelley [6], a unidirectional hybrid composite consisting of both high elongation and low elongation components can continue to carry the total load after failure initiation in the low elongation component if the following condition is satisfied:

$$V_{HE} \geq [\sigma_{LU}/(\sigma_{HU} + \sigma_{LU} - \sigma_H^1)] \tag{2}$$

where V_{HE} = fiber volume fraction of the high elongation component

σ_{LU} = failure stress of low elongation fiber

σ_{HU} = failure stress of high elongation fiber, and

σ_H^1 = stress of the high elongation fiber at the failure strain of the low elongation component.

In this study we have modified equation (2) using the methodology established by Ko et al [7] to guide our design of the braided hybrid composites.

EXPERIMENTAL

To demonstrate the design concept and to verify the analytical predictions, a series of braided hybrid FRP bars with a nominal diameter of 5 mm. were fabricated. Two basic fibers Kevlar 49 and carbon fiber were used. A very high modulus carbon fiber Type P55 was used in order to produce a high initial modulus for the composite rebar. The Kevlar yarns were used for the braided sleeve whereas the carbon yarns were used for the core structure. In order to achieve reproducibility, a computerized braiding system developed at Advanced Product Development, Inc. was used. This system allows the incorporation of the rib effect automatically, as well as control of braiding angle and fiber volume fraction. To facilitate composite production, the braided structures were fabricated by in-line braiding and pultrusion (Figure 5).

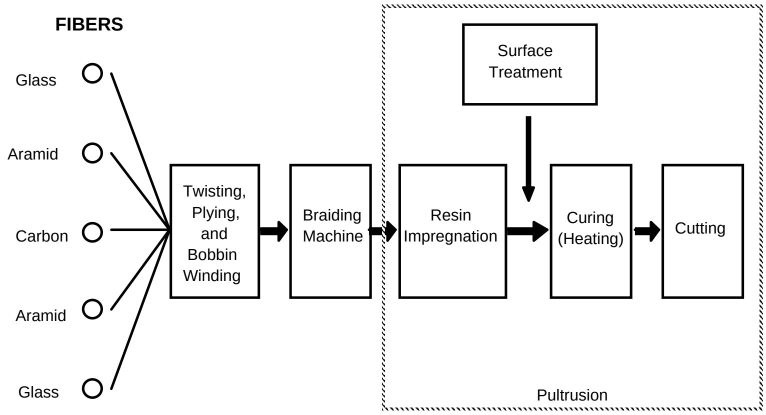

Fig. 5 Schematic of Production of Hybrid FRP Bars.

Tensile Behavior of the Composite Rebar

Three 5 mm. tensile specimens 42.5 cm. long were cut from the FRP bars production line with a water-cooled diamond saw. Simple tensile testing of the braided FRP bars were performed according to ASTM D3039 (1993) standards for tensile strength testing using a Tinius-Olsen T10000 bench top universal testing machine. Cast epoxy beveled tabs were developed to fit the specimen into the tensile grips and minimize stress concentration on the test specimen. The specimen ends were casted in aluminum molds with Epon 828 with room temperature curing agent, Epi-cure 3061. A Tinius-Olsen extensometer with a 50 mm gage length was equipped with film clamps to minimize the stress concentration from clamping onto the FRP specimens.

All specimens composite bars failed in a similar manner, near the middle of the specimen length. The stress-strain curve exhibited a bilinear behavior with a relatively high initial slope before reaching a pseudo yield point. The yield strain was approximately equal to the ultimate strain of the core yarn. The initial elastic modulus of the braided composite bar was found to be predictable using the rule of mixtures when the geometric effects such as yarn twist, yarn crimp and braiding angle are taken into account. After reaching the yield point, a small drop of stress was experienced by the composite bar before further build up of stresses. The progressive breaking of the small braiding yarns were visible and they occurred in a sequential manner. Each breakage corresponded to a drop in the stress-strain curve. Most of the subsequent drops occurred at a higher stress level than the previous ones. The hybrid FRP bars were able to withstand increasing stress significantly higher than the first yield stress. When the strain was increased to the value near the ultimate strain of the sleeve yarn, the hybrid FRP bars reached their ultimate strength and failed suddenly. Between the first yield stress and the ultimate strength, the stress-strain curve exhibited the transition range where many drops in stress level occurred. This strain harden slip-stick behavior is due to the progressive failure of core and sleeve yarns which creates a ductile failure mechanism for the composite rebar.

A comparison of the theoretical and the experimental tensile stress-strain curves are shown in Figs. 6. As can be seen from Figs. 6, the agreement between the theoretical and experimental curves is good in the initial modulus and in the post yield modulus. The mean slope of these curves paralleled the slope of the theoretically predicted curves. The analytical model however predicts a higher drop in stress at yield.

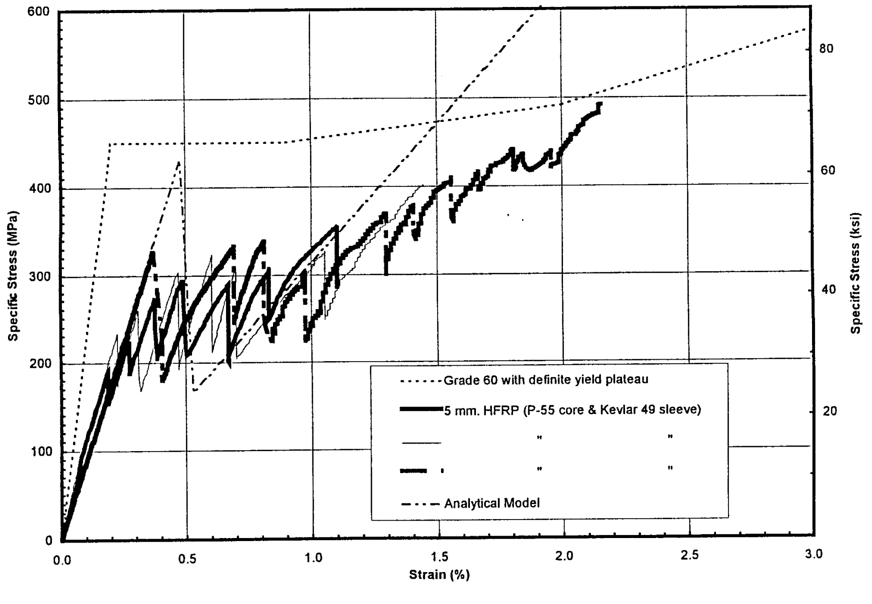

Figure 6. Experimental and Theoretical stress Strain Curves of Braided Composite Bars

Flexural Behavior of Braided Composite Reinforced Concrete

Three concrete beams (50 mm x 100 mm in section and 1.2 m long), each reinforced with 4 braided hybrid FRP bars were prepared for four point flexure test to failure. The composite bars had a 5 mm nominal diameter and they were placed on the bottom side of the concrete beams. All the beams were casted at the same time and moisture cured for at least 28 days before testing. These beams were designed to have the same ultimate strength capacity as the reference steel reinforced beam. Steel stirrups were used in each beam in order to limit the study to the effects of tensile reinforcements. A Tinius-Olsen T10000 bench top universal testing machine was used with three dial gages and three linear-variable-differential-transformers (LVDT) for monitoring the deflection and the curvature of the beams. The load vs. deflection characteristics of this beam series is shown in Fig. 7. It can be seen that all three FRP reinforced beams failed in a similar manner. The FRP reinforced beams exhibit linear elastic deformation in the initial part of the load-deflection curve, follows by a pseudo plastic deformation exhibiting the strain hardening characteristic similar to that observed in steel reinforced concrete beams. The ductility indices, as determined by computing the ratio of ultimate to yield strain in the flexural load-deformation curve, of the braided FRP reinforced beams were founded to be greater than 5 . This is remarkably similar to that of the steel reinforced concrete beam. Such high ductility has yet to be achieved with the presently available linearly elastic FRP systems!

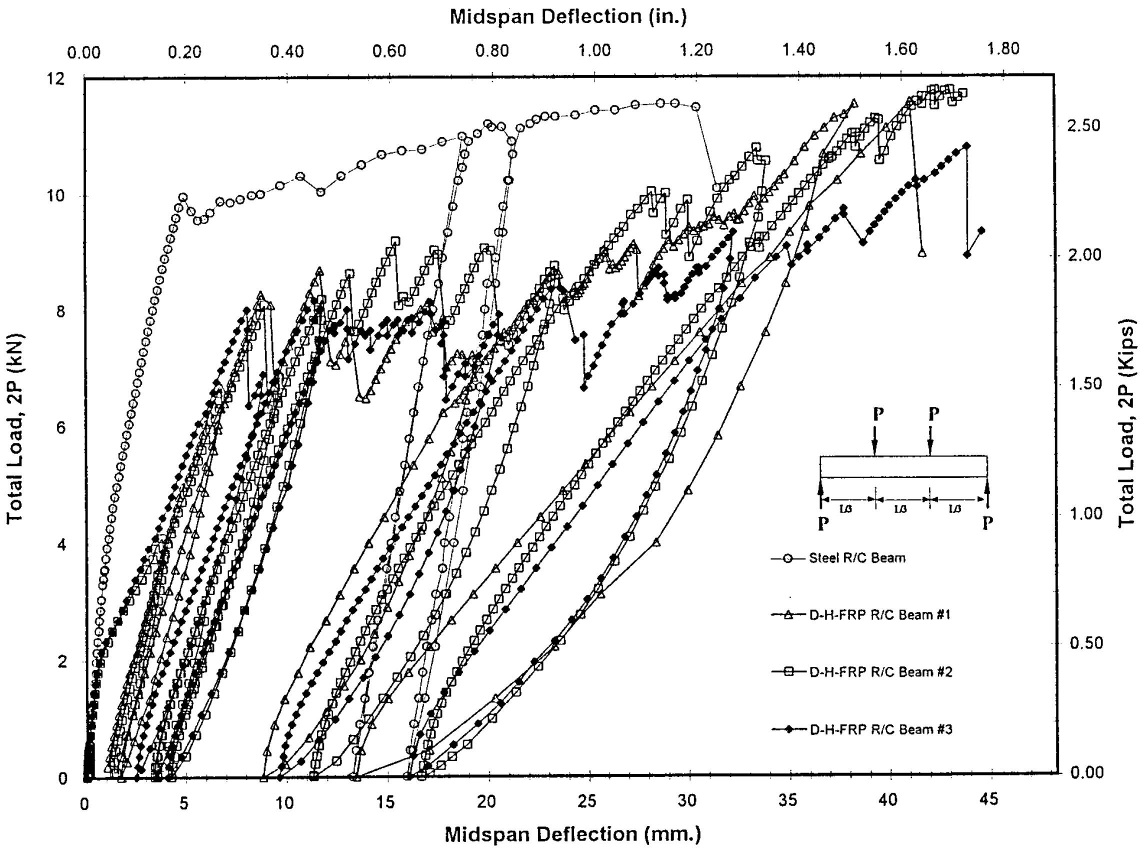

Figure 7. Load Deflection Behavior of Braided Composite Reinforced Concrete Beams

CONCLUSIONS

Guided by a fiber architecture based model (the FGM), a series of experiments were designed and carried out using carbon fiber as core yarr and Kevlar fiber for braiding yarns. An on-line braiding pultrusion process was constructed to provide a continuous process to produce the hybrid fiber reinforced epoxy matrix rebar. The braided composite rebar specimens of various diameters were tested according to ASTM D638 using a 50mm gage length. It was shown, as predicted by the FGM, that the composite rebar failed in a ductile manner after an initial region of elastic response. The slip-stick, pseudoyield behavior can be attributed toi the in situ balancing of elongation of the various fibers/matrix components in the hybrid composite. This preliminary result suggests that the proper selection of higher modulus core fibers coupled with a well balanced elongation of the components in the braided fiber assembly will generate a stress-strain curve for the composite rebar approaching that of the steel rebar. Further experiments on the flexural response of concrete beams reinfroced by the braided composite rebar confirmed that metal;like ductility can be engineered using composite rebar. With the availability of a low cost manufacturing process and a well established design tool, the adaptation of braided composite rebar for large scale civil infrastructure applications will be realized when high performance fibers such as carbon and aramids are available at a low cost.

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