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ScienceDirect

Composite Structures 84 (2008) 114–124

COMPOSITE STRUCTURES

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Application of polymer composites in civil construction: A general review

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Abstract

Different applications of fiber reinforced polymer composites (FRPCs) for external strengthening in civil construction are reviewed in this paper. Experimental as well as analytical and numerical research contributions have been focussed in the review. The main structural components such as beams, columns and beam-column joints, have been reviewed and structural behavior of each component is discussed briefly. Finally, general concluding remarks are made along with possible future directions of research.

Keywords: FRPC; CFRPC; GFRPC; AFRPC; Rehabilitation; Strengthening

1. Introduction

Advanced composite materials have found expanded use in aerospace, marine and automobile industries during the past few decades (1960 onwards) due to their good engineering properties such as high specific strength and stiffness, lower density, high fatigue endurance, high damping and low thermal coefficient (in fiber direction), etc. Recently, civil engineers and the construction industry have begun to realize potential of composites as strengthening material for many problems associated with the deterioration of infrastructures. Over the last decade, an increase in the application of FRPCs has been seen in construction industry because of their good engineering properties. Further, these are being considered as a replacement to the conventional steel in reinforced concrete structures due to continuing drop in the cost of FRPC materials. Various aspects of FRPC materials including guidelines for selection of polymer adhesives for concrete have been highlighted by ACI Committee-503 [1] and Uomoto et al. [2]. Issues related to selection of materials have also been discussed by Karbhari [3]. Einde et al. [4] and Bank et al. [5] have presented a summary of applications of FRPC material in civil engineering whereas general design guidelines for FRPC application can be found in Bakht et al. [6], ACI Committee 440 [7] and Nanni [8].

Use of FRPC sheets for strengthening and rehabilitation of concrete structures has attracted considerable interest [9–12]. First applications of composites were in the form of rebars and structural shapes. Later, FRPC laminates were used for strengthening of concrete bridge girders by bonding them to the tension face of girder [13] as well as for retrofitting of concrete columns [14].

FRPC are available in the form of rods, grids, sheets and winding strands. Review of literature up to 1996 can be found in ACI Committee 440 [15]. Another general review on class of materials including FRPCs used in civil construction was presented by Bakis et al. [16]. They divided the whole review into structural shapes, internal reinforcement, externally bonded reinforcement, bridge, standards and codes. A review on shear strengthening of RC beams with FRPCs was done by Deniaud and Cheng [17], Bousselham and Chaallal [18]. Review related to the bond-slip model for FRPC sheet/plate bonded to concrete have been presented recently by Lu et al. [19] and review for upgrading of beam-column joints with FRPC can be found in Engindeniz et al. [20]. A large volume of literature

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0263-8223/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruct.2007.06.007

now exists on applications of FRPCs in construction industry. However, literature up to July 2005 is considered here for general classification.

The main objectives of the paper are to classify the available literature (analytical/experimental) and to discuss the effects of various parameters such as fiber type, thickness, fiber angle, concrete strength, etc. Discussion is kept on a descriptive level and reader is advised to refer to the cited references for details of parameters and mathematical models.

2. Repair and rehabilitation of structural elements

Majority of rehabilitation works consist of repair of old deteriorating structures, damage due to seismic activities and other natural hazards. Structural strengthening is also required because of degradation problems which may arise from environmental exposure, inadequate design, poor quality construction and a need to meet current design requirement. Therefore, structural repair and strengthening has received much attention over the past two decades throughout the world. Recent experimental and analytical research have demonstrated that the use of composite materials for retrofitting existing structural components is more cost-effective and requires less effort and time than the traditional means.

Historically, composites were first used as flexural strengthening materials for reinforced concrete (RC) bridges, as confining reinforcement for RC columns [21] and unreinforced masonry walls [14] against possible earthquake forces. Apart from strengthening of bridge girders, columns and walls, composites are also used in bridge decks and in cable stayed bridges. Strengthening of beams, columns and beam-column joints are discussed in the sequel.

2.1. Strengthening of RC beams by using FRPC

One of the most popular techniques for strengthening of RC beams has involved the use of external epoxy-bonded steel plates [22,23]. It has been demonstrated experimentally that flexural strength of a structural member can increase by about 15% with this technique. Steel bonding technique is simple, cost-effective and efficient. However, it was found that it suffers from a serious problem of deterioration of bond at the steel and concrete interphase due to corrosion of steel. Other common strengthening technique involves construction of steel jackets which is quite effective from strength, stiffness and ductility considerations. However, it increases overall cross-sectional dimensions, leading to increase in self-weight of structures and is labour intensive. To eliminate these problems, steel plate was replaced by corrosion resistant and light-weight FRPC plates. FRPCs help to increase strength and ductility without excessive increase in stiffness. Further, such material could be tailored to meet specific requirements by adjusting placement of fibers.

2.1.1. Flexural behavior of RC beams strengthened by FRPC

Flexural strengthening of RC beams using composites can be provided by epoxy bonding of FRPC plate to the portion of elements in tension, with fibers parallel to the principal stress direction. If fibers are placed perpendicular to cracks, a large increase in strength and stiffness is achieved compared to situation where fibers are placed oblique to the cracks [24,25]. Considerable experimental research has been conducted for strengthening of RC beams with glass, carbon or aramid FRPCs to investigate serviceability, strength enhancement, cracking patterns and failure-modes, etc. [26–52]. Literature review has shown that nearly 40% strength enhancement is possible for RC beams strengthened with glass fiber reinforced polymer composite (GFRPC) whereas around 200% strength enhancement is achieved with carbon fiber polymer composites (CFRPC). In addition to the fiber type, flexural performance of strengthened RC beams is affected by several factors such as modulus of elasticity of FRPC and its center of gravity location relative to the neutral axis [53], width of laminate [38], length of laminate [53], amount of main and shear reinforcement [54], number of FRPC layers [40], level of loading [55], FRPC configuration [56,57], concrete strength and cover [58], damage and loading condition [43,59], etc.

FRPC material has relatively low modulus of elasticity and linear stress–strain relation up to rupture with no definite yield point. As a result strengthened beams generally exhibit large deflection, wide as well as closer cracks and brittle failure mode [60,61]. Effect of reinforcement ratio on cracking moment, crack spacing, cracking patterns and crack width was experimentally investigated by Masmoudi et al. [62]. A variety of indices including deformability ratios [56], energy ratios [63] have been proposed to measure ductility because definition of ductility for steel reinforced concrete beam can not be directly applied to the FRPC strengthened RC beams. Experiments have indicated catastrophic failure of strengthened beams due to low ductility. Spadea et al. [36] and Bencardino et al. [64] have suggested anchorage system to increase ductility, which is not affected by the change in the loading rate [42]. Grace et al. [65,66] performed experiments by using innovative triaxially braided ductile fabric which was reported to increase ductility. It was reported by Salom et al. [67] that torsional capacity of RC beams can be increased up to 70% with the help of FRPC strengthening. Ghobarah et al. [68] demonstrated experimentally that fully wrapped beams performed better than only strips and 45° orientation of fibers is more effective for upgrading torsional resistance. To avoid the extensive time consuming process by employing semi-skilled labour for application of FRPC to concrete surface, a commercial off-the-shelf-actuated fastening system was used by Lamanna et al. [69] in experimental study by considering different fasters' length and layouts. The technique was reported to be effective for bonding compared to conventional techniques. This method also increased ductility over the conventionally bonded method and took around 1/8 of time compared to the conventional method.

The quasi-static behavior of flexural members strengthened with FRPC is well documented in literature. However, there is a gap in knowledge on the effect of impact and fatigue loadings on the beam. Repeated loading can lead to internal cracks in a member which can alter its stiffness and load carrying characteristics. Barnes and Mays [70], Erki and Meier [71], Shahawy and Beitelman [72], Masoud et al. [73], Heffernan and Erki [74], Brena et al. [75] and Bonfiglioli et al. [76] presented experimental results for static and fatigue failure of beams strengthened with CFRPC sheets. It is observed from the results that fatigue life of reinforced concrete beams could be significantly enhanced through the use of externally bonded CFRPC laminate and it is largely dependent on the stress range applied to steel reinforcement.

The experimental studies discussed above have been substantiated by analytical approach at macro level. In all the simplified analytical models, strain compatibility has been used to predict flexural behavior either by ultimate load method or working stress method [9,29,46,77–79], wherein issues related to rational design of externally strengthened RC beams for interpreting major modes of failure including flexural, interface separation, flexural-shear crack and concrete cover rip off have been addressed. Parametric study was performed by Picard et al. [80], which highlights the importance of concrete compressive strength whereas An et al. [81] emphasized on amount of the main reinforcement.

Stiffness of concrete structures usually starts to degrade, as cracks are developed in concrete. Stiffness degradation due to cracking of concrete is not considered in the simplified linear elastic models. Furthermore, contrary to actual behavior, stress–strain curve of concrete is assumed to be linear in elastic models. Therefore, it is necessary to account for the crack generation and stiffness degradation in refined non-linear analysis. Studies in this direction were performed using finite element method to capture flexural behavior of strengthened RC beams [82–86] by assuming perfect bonding between concrete-steel and concrete-FRPC laminate. Thomsen et al. [87], for example, developed non-linear finite element models using bond-slip relationship between concrete and FRPC to evaluate delamination failure mode. On the other hand, Colotti et al. [88] proposed a theoretical model based on truss-analogy. A non-linear analysis was performed by Aiello and Ombres [89] considering tension stiffening and force transfer between concrete and FRPC to investigate serviceability (cracking and deformability) criteria. Yang et al. [90] presented fracture mechanics based finite element analysis to capture debonding failure. The method was observed to successfully simulate concrete cover separation failure mode in FRPC strengthened RC beams. Sato and Vecchio [91] developed a simple equation to estimate crack spacing, its width and tension stiffening effect.

2.1.2. Shear behavior of RC beams strengthened by FRPC

Shear strengthening of RC elements can be provided by epoxy bonding of FRPC materials with fibers parallel, as practically possible, to the direction of the shear stresses. Various experimental and analytical works related to shear strengthening of beams with different FRPC laminates for uncracked/cracked RC beams are reported by Sharif et al. [92], Chajes et al. [93], Chaallal et al. [94], Triantafillou [95], Deniaud and Cheng [96], Lees et al. [97], Pellegrino and Modena [98], Adhikary and Mutsuyoshi [99], Zhang and Hsu [100]. It was observed that the shear strength of virgin beam can be increased by 60–120% using FRPC sheets. Fiber orientation may be vertical or perpendicular to the shear cracks. Shear contribution to the total shear capacity of strengthened RC beams depends on several parameter including surface preparation, composite fabric shear reinforcement ratio, amount of main and shear reinforcement, shear span to effective depth ratio, strength of FRPC, number of FRPC layers, wrapping schemes, depth of sheet across beam section [99,101–103]. U-wrap of sheet provided the most effective strengthening for RC beams with about 119% increase in shear strength.

The ultimate resistance of beam can not be taken into account by simple superposition of shear capacity contributions because of complex interaction between concrete, steel and FRPC. This has been reported to be the major obstacle in development of an analytical formula that can correctly predict the ultimate load of strengthened beams in shear [101,102]. By assuming a perfect bond between concrete and FRPC, Malek and Saadatmanesh [104,105] developed equilibrium and compatibility equations using truss analogy method. Further, compression field theory was used to calculate shear force resisted by FRPC plate, crack inclination angle, stresses in stirrups before cracking as well as after formation of crack. Khalifa et al. [106] reviewed research on shear strengthening and proposed a design algorithm to compute contribution of FRPC to shear capacity of RC beams. Another group of researchers [107–109] have presented analytical models to calculate the ultimate shear capacity of strengthened beams by assuming linear elastic behavior of FRPC materials. Review on different shear design methods can be found in Micelli et al. [110] with commentary on adequacy of each method. However, numerical modeling of shear strengthened RC beams with FRPC has not yet been addressed adequately in open literature.

2.1.3. Durability of RC beams strengthened by FRPC

Seasonal and daily temperature variations cause freezing and thawing cycles, differential thermal expansion between concrete and FRPC substrate, resulting in premature plate separation and ultimately failure of strengthened system. Cross-directional (matrix dominated) properties such as transverse tensile/compressive strength and in-plane shear were found to be highly affected by environmental effects but fiber was less sensitive to it.

Karbhari and Engineer [111], Karbhari and Zhao [112], Sen et al. [113], Sen et al. [114,115], Green et al. [116], Aiello et al. [117], Bisby and Green [118], examined effect of short-term environmental exposures on externally strengthened RC beams with FRPC by considering different types of fibers, different wet/dry and freeze/thaw cycles, etc. It was observed that degradation occurs primarily at the level of resin in contact with concrete and reduction in strength is nearly 80–90% when strengthened system is subjected to high temperature range [119]. A simple analytical model is proposed by Bisby and Green [118] to predict bond failure because of thermal load. Long-term behavior of strengthened beams is very important and work in this direction was reported by Karbhari and Engineer [111], Plevris and Triantafillou [120], Xie et al. [121], Karbhari and Shulley [122], Saadatmanesh and Tannous [123], Soudki and Sherwood [124] under various conditions like dry/wet temperature, acids, alkali, etc. Creep and Shrinkage of strengthened beam was studied by Plevris and Triantafillou [120] and Bank et al. [125] who presented different test methods to study long-term behavior of FRPC structures along with different theoretical models and experimental techniques to predict effects of different environmental conditions. The combined effect of harsh environment and fatigue loading was studied by Gheorghiu et al. [126] on flexural behavior. Recently, Grace and Singh [127] proposed strength reduction factors associated with various independent environmental conditions like 100% humidity, salt water, alkali solution, freez-thaw, thermal expansion, etc. Effect of chloride content and rebar corrosion was studied by Wang et al. [128] whereas Maaddawy et al. [129] developed mathematical model for prediction of inelastic response of strengthened RC beams by taking into account reduction of steel area due to corrosion and its effect on concrete-steel interface.

2.1.4. Bond and development length of FRPC

Bond of external FRPC reinforcement to the concrete substrate is a critical factor for effectiveness of strengthening as delamination of FRPC laminate from concrete surface can cause failure of concrete structure. Arduini and Nanni [33], Arduini et al. [130], Buyukozturk and Hearing [131], Swamy and Mukhopadhyaya [132], Nakaba et al. [133], Nguyen et al. [134], Sebastian [135] and Lorenzis et al. [136] performed experimental studies to address bonding issue of FRPC plates. Experiments with different epoxies were also conducted by Saadatmanesh and Ehsani [26] who suggested use of rubber toughened epoxies. Bond between FRPC and concrete surface also depends on preparation of concrete surface (water jet or sand blasting), concrete compressive strength and effective bond length [137], fibers stiffness and shape of stress distribution [134], etc. Considerable research was performed by using anchor bolts or U-shape fiber fabrics at the end [32,132,138,139] to avoid premature failure of FRPC plates from concrete surface. This technique increases ductility but original concrete gets disturbed because of anchor bolt. This can be avoided by using U-shape fabrics which provide ductility as well as increased shear strength.

2.2. Strengthening of RC columns using FRPC

Wrapping of FRPC sheets around concrete columns is a promising method for structural strengthening and repair. Application of fabric sheet is quite easy, requiring no specialized tools; thus technique is of practical interest. One of the deficiencies in concrete columns is the lack of lateral confinement and low energy absorption capacity. External confinement of concrete significantly enhances strength, ductility and energy absorption capacity of concrete specimens by constructing additional RC cage around existing columns or using grout-injected steel jackets [140,141].

2.2.1. Axial behavior of RC columns strengthened with FRPC

A number of studies including Demers et al. [142], Nanni et al. [143], Saadatmanesh et al. [144], Seible et al. [145], Hanna and Jones [146], Xiao and Wu [147], Bousias et al. [148], Matthys et al. [149], Carey and Harries [150], Harajli [151] have investigated the axial behavior of concrete with different FRPC jackets from strength and ductility point of view. FRPC wraps consisting of carbon, aramid and glass fibers, bonded with epoxy resins have been successfully applied for seismic rehabilitation of bridge piers in USA and Japan [152]. Various parameters affecting the performance of confined columns' systems including concrete strength, depth-to-width ratio [153–155], longitudinal reinforcement, stirrups, corrosion of steel, concrete damage [156], fiber type, wrap angle [157], thickness of wrap [158], slenderness ratio [159], deformability of the concrete, stiffness of the jacket in the lateral direction [160], concrete dilation ratio [161], geometric and loading imperfection [162], etc. have been investigated by researchers. Application of pretensioned FRPC sheet for strengthening of RC columns has been performed by Mortazavi et al. [163].

Shape of column section is a critical parameter affecting confined strength of column. The most effective confinement is obtained for circular columns rather than rectangular and square columns [164–166]. Square or rectangular sections engage high confining pressure at their corners but little pressure on their flat sides, therefore the cross-section is not effectively confined, resulting in a lower increase in strength [142]. In order to increase the effectiveness of confinement for rectangular and square columns, the column section can be modified into the elliptical section, that is, the corners have to be rounded to prevent premature failure but radius is limited because of internal longitudinal reinforcement [164]. Shear strength of RC columns strengthened with CFRPC was studied by Ye et al. [167] who concluded that shear strength of RC column can be effectively increased with external strengthening.

Structural behavior of concrete columns confined by FRPC was investigated by many researchers [168–176] using analytical models to predict stress–strain behavior between confined concrete and FRPC wraps. Analytical models are based on deformation compatibility and equilibrium of forces between concrete and FRPC. Mander et al. [140], for example, developed an analytical model to calculate increased compressive strength of concrete in RC column due to confining pressure provided by transverse reinforcement. This model was further modified by Teng and Lam [166], Wang and Restrepo [170], Tan [171], Saadatmanesh et al. [177] to analyze behavior of RC columns wrapped with FRPC of various cross-sections like circular, elliptical, square and rectangular. Mirmiran and Shahawy [178] modified model suggested by Mander et al. [140] by considering strain energy approach. A design procedure was proposed by Theriault and Neale [179] to improve axial load capacity of circular and rectangular columns confined with FRPC wraps. Chaallal et al. [180] presented a stress–strain curve by considering fibers in axial and lateral direction for axially loaded rectangular short columns confined with FRPC jackets. Lam and Teng [181] developed a stress–strain curve with fibers in hoop direction only, which can be directly used in design. This model is applicable for concrete confined by all types of FRPC as well as steel. Recently, comparisons of various available confinement models have been presented by Bisby et al. [182].

2.2.2. Seismic behavior of RC columns strengthened by FRPC

A large lateral cyclic earthquake force can degrade strength of concrete and reinforcing bar that can result in premature failure of column. Retrofitting of column components to withstand earthquakes is a recent and widespread task and one of the more complex engineering challenges. Seismic resistance of retrofitted RC columns improves significantly because of confining action of the FRPC wraps [183–185]. The technique has been observed to improve displacement ductility as well as strength. Further, repaired specimens exhibit lower rate of deterioration under large reversal cyclic loading than the virgin columns [186]. Amount of external reinforcement required depends on level of axial load and extent of damage.

Xiao and Ma [187] developed an analytical model by considering the bond-slip deterioration of lap spliced longitudinal bars for seismic assessment and retrofit design. A non-linear finite element analysis was performed by Parvin and Wang [188] on FRPC jacketed RC column under combined axial and cyclic lateral loading. Finite element analysis results indicated that FRPC fabric showed significant improvement in strength as well as ductility in potential plastic hinge location at the bottom of column. Elsanadedy and Haroun [189] proposed seismic design procedure for circular lap-splice reinforced RC column upgraded with FRPC jackets based on moment curvature analysis with inclusion of bond-slip mechanism.

2.2.3. Durability of RC columns strengthened by FRPC

Environmental exposures to conditions such as freeze-thaw can potentially affect confining material (FRPC) as well as confined concrete and the bond between composite and concrete. Exposure of various environmental conditions usually resulted in decrease of strength, stiffness, and possibility of change in failure mode [190–195]. Toutanji and Balaguru [196,197] reported that CFRPC is superior to GFRPC under harsh environment. It was observed that exposure to wet–dry environments has little effect on strength and ductility of CFRPC wrapped specimens. On the other hand, GFRPC wrapped specimens exhibited about 10% reductions in strength. However, CFRPC and GFRPC wrapped specimens are equally susceptible to freeze-thaw cycles. Another group of researchers [198–200] performed experimental studies on strengthening of corrosion damaged RC columns by using different types of fibers and concluded nearly 20% increase in load carrying capacity with 50% decrease in rate of post repair corrosion but the strengthened system exhibited somewhat reduced ductility because of loss of reinforcement due to corrosion process.

2.3. Strengthening of RC beam-columns joint by FRPC

Performance of beam-column joints is very important in determination of the ability of structure to withstand large earthquake and other lateral loads. Shear failure of beam-column joints has been identified to be the principal cause for collapse of many moment resisting frame buildings during recent earthquakes. Shear failure during an earthquake have been attributed to inadequate transverse reinforcements at the joint and weak-columns/strong-beam design. A study on external beam-column joint has shown failure of the structure by beam hinging [201] if axial load on the columns is high and beam reinforcement is less than 1.2%. Several techniques have been applied to strengthen beam-column joints, including uses of concrete jackets, bolted steel plates [202]. However, it is difficult to provide effective confinement in the rehabilitation of beam-column joints. Use of FRPC for strengthening of dilapidated reinforced concrete structures has increased in recent years. However, behavior of beam-column connection is complex and still not completely understood. External FRPC reinforcement is an effective method to increase moment carrying capacity of beam-column connection by about 60% [203] and shear capacity of the joint by about 35% [204,205].

Various researchers have conducted experiments on strengthening of beam-column joints from a ductility point of view to understand failure mode with and without anchorage using different types of FRPC with variable angle of fibers and numbers of layers [205–210]. It has been observed that fibers inclined at 45° to the direction of principal planes are most effective for strengthening in the joint region. Pulido et al. [211], Shannag and Alhassan [212] performed experimental studies on seismic behavior of beam-column joints.

Pulido et al. [211] also proposed a simple model and implemented confined concrete stress–strain curve in pushover analysis.

3. General concluding remarks

Application of FRPCs in civil construction both in repair and retrofitting has been reviewed. Both experimental and analytical works have been included. Application of FRPCs for slab are not discussed here for the sake of brevity; only few pertinent literature is listed at the end [213–229]. Following general concluding remarks are made:

- Majority of research has been concentrated on repair of existing structures. Studies have demonstrated improvement in ultimate capacity and stiffness leading to reduction in the overall maximum deflection and strains. To utilize the full capacity of the FRPC plate and to prevent the plate separation, plate anchorage system can be advantageously used to improve bond strength between FRPC and concrete as it is the key factor affecting the overall integrity of beams.
- Confinement to concrete columns provided in the form of wrapping of FRPC fabrics or tubes has proved extremely beneficial. This has achieved enhancement in strength, load carrying capacity, energy absorption, ductility, stiffness and improvement in failure-modes and hence, proved extremely beneficial for concrete columns. Extent of benefit, however, depends upon many factors such as type, amount, and direction of confining material, size, shape and loading condition of the column.
- Externally bonded FRPC reinforcement is a viable solution towards enhancing strength, stiffness and energy dissipation characteristics of reinforced concrete beam-column joints subjected to regular as well as seismic loads. It also enhances shear capacity and improves overall damage control.
- Use of FRPC improves load carrying capacity and energy absorption capability of slabs reinforced with FRPC. General cohesiveness, stress transfer capability across the crack improves due to strengthening, which delays crack formation and thus FRPC reinforcement is able to achieve its full potential of strengthening of slabs.
- Research is needed to determine the endurance limit of FRPC during fire, fatigue performance of strengthened structure, effect of chemical and ultra-violet radiation on FRPC, etc. Long term studies are required to examine effect of alkalinity, temperature, etc. on resins and fibers. Effect of freeze-thaw cycling under sustained load is also not understood fully. Width of laminate is not entirely effective in resisting moments in the end zone; behavior of beams with varying widths of laminate towards the end can also be investigated. Research is needed to study behavior of short as well as long columns under combined axial and bending moment. Column subjected to dynamic loading condition is another important area for consideration. Experimental and analytical studies are required to understand behavior of beam-column joints from torsion, ductility and durability points of view.

Acknowledgements

Partial support of USIF Indo-US Collaborative Sponsored Research Project IND104 (95IU001) is gratefully acknowledged. Constructive comments of the reviewer are also gratefully acknowledged.

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