Fracture Mechanics of Concrete Structures
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MATERIALS AND DESIGN CONSIDERATIONS IN FRP REHABILITATION OF CONCRETE STRUCTURES

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Abstract
Fiber reinforced polymer matrix composites are increasingly being considered for use in repair, strengthening and retrofit of concrete structures. The technology is now at a point where its future acceptance will depend primarily on the availability of validated design guidelines based on accepted performance criteria, and on the economic competitiveness of these technologies as compared to conventional methods of rehabilitation. The myriad possibilities of reinforcement and resin combinations, and processing paths possible with PMCs make it important that the guidelines include provisions for materials and process selection, failure mechanisms, and design detailing. The efficiency of the rehabilitation measure and its efficacy depend not just on the application of the composite to the structure, but rather on the development of appropriate design detailing measures based on mechanics of bond transfer, failure modes/fracture mechanisms, and systems structural response. This paper discusses a number of these aspects with specific emphases on materials and processes, integrating aspects from the areas of mechanics, materials science of composites and polymers, and civil engineering design and detailing practice.
Key words: Composites, rehabilitation, retrofit, concrete

1 Introduction

In addition to deterioration and degradation caused through aging, weathering of materials, and accidental damage to structures, our traffic needs have increased dramatically over the past two decades with transportation of goods and services being conducted on a global, rather than local basis, resulting in a growing need for the widening of our highway systems to accommodate more lanes, and for the renewal of existing structures to carry heavier loads at higher speeds. Enhanced understanding of structural response has led to the establishment of new design codes and the need to rehabilitate existing structures to ensure their safety. It is increasingly becoming apparent that deteriorating transportation related systems such as roads and bridges have a tremendous impact on society in terms of socio-economic losses resulting from delays and accidents. Conventional materials such as steel, concrete and wood have a number of advantages, not the least of which is the relatively low cost of materials and construction. However, it is clear that conventional materials and technologies, although suitable in many cases, and with a history of good applicability, lack in longevity in some cases, and in others are susceptible to rapid deterioration, emphasizing the need for better grades of these materials or newer technologies to supplement the conventional ones used. In all such (and other) cases, there is a critical need for the use of new and emerging materials and technologies, with the end goal of facilitating functionality and efficiency.

Based on their high strength- and stiffness-to-weight ratios, corrosion resistance, environmental durability, and inherent tailorability, fiber-reinforced polymer matrix composites are increasingly being considered for use in the rehabilitation of existing infrastructure, and for the construction of new structures. The efficacy of use of these materials depends largely on the appropriate selection of constituents (fiber, resin and filler), processing method, and design detailing with respect to the specifics of the application, including the surrounding environment. The structural effectiveness of fiber reinforced polymer (FRP) matrix composites in the rehabilitation of concrete structures has repeatedly been demonstrated world-wide through large-scale tests as well as field demonstrations. Applications for the use of these materials range from the strengthening and retrofit of reinforced and unreinforced masonry walls, seismic retrofit of bridge and building columns, repair and strengthening of beams, girders and slabs, and the rehabilitation of structures such as slabs after post-construction modifications such as cut-outs for lift-wells are made in them.

The ease of application of FRP composites makes them extremely attractive for use in civil infrastructure applications, especially in cases where dead weight, space, or time restrictions exist. However, it is important that engineers and designers be aware of details related to their properties and characteristics, other than those at a very simplistic level. Although FRP composites can have strength levels significantly higher than those of steel, and can be formed of constituents such as carbon fibers which have moduli equal to or greater than the modulus of steel, it is important to note that the limit of use is often dictated by strain limitations. FRP composites in general behave in linear elastic fashion to failure, without any significant yielding or plastic deformation induced ductility as seen in steel or reinforced concrete. Additionally, it should be noted that unlike reinforcing steel, some fibers, such as carbon fibers, are anisotropic, having different properties in the longitudinal (i.e. along the length of the fiber) and transverse directions. For example, although the tensile modulus for T300 carbon fibers in the longitudinal direction is 230 GPa, in the transverse direction it is only about 40 GPa, a fact that must be considered when designing with fibers or fabrics that have to conform to tight radii and corners. In the case of aramid fibers, the fiber structure itself tends to fibrillate on the compression side, again emphasizing the need for special consideration around edges and corners. Furthermore, although the carbon fiber has a negative coefficient of thermal expansion in the axial direction, it has a value of $+10 \times 10^{-6}$ /°C in the transverse direction.

Whereas the environmental durability of FRP composites is often touted as being one of its major advantages over conventional materials, it must be noted that environmental durability is significantly affected by the choice of constituents, and details of the process used to fabricate the composite. Data on systems such as E-glass reinforced polyester or vinylester, carbon reinforced vinylester, and other lower cost systems that are likely to be used in these applications is sparse, unlike the extensive data bases available for aerospace grade composites such as the AS4/3501-6 and T300/5208 type systems. Further it is important to note that exposure to a variety of environmental conditions, can dramatically change failure modes of the composites, even in cases where performance levels remain unchanged. In other cases, exposures can result in the weakening of the interface between FRP composites and concrete causing a change in failure mechanism and sometimes a dramatic change in performance. This paper discusses materials and process related aspects vis-à-vis seismic retrofitting of columns and the strengthening of slabs.

2 Seismic Retrofit of Columns

There is considerable activity in both the US and Japan on the development of techniques for the rapid and cost-effective retrofit of concrete columns to render existing substandard designs safe under seismic excitation. Concrete columns which need to be retrofit are commonly deficient in flexural ductility, shear strength, bar buckling restraint and/or lap splice clamping. The use of jackets/wraps around the column induces lateral confining stresses in the concrete as it expands laterally in the compression zone as a function of the high axial compressive strains, or in the tension zone as a function of dilation of lap splices, or through the development of diagonal shear cracks. FRP composite jacketing techniques have been shown to have performance capabilities comparable and in some cases better than that shown by columns retrofitted through the application of steel casings as is done conventionally. Design equations for the use of these jackets have been developed by Seible et al. (1997) and have been validated based on scale and full-scale testing. The thickness of the FRP composite required depends on the design requirements to correct the failure modes expected under seismic load/deformation input, and a comparison of the use of various material combinations is shown in Table 1. Different types of FRP composite jacketing systems, as shown schematically in

Table 1: Comparison of Hypothetical Jacket Thicknesses

Material	Properties* Vf = 60%	Normalized Jacket Thickness			
		Shear Strengthening $t = a_v / (E . D)$	Plastic Hinge Confinement $t = a_c.D/(f_{ju}.e_{ju})$	Bar Buckling Restraint $t = a_b . D / (E)$	Lap Splice Clamping $t = a_v . D / (E)$
E-glass/Epoxy	E = 45 GPa σ = 1020 MPa ε = 2.3%	1	1	1	1
S-glass/Epoxy	E = 55 GPa σ = 1620 MPa ε = 2.9%	0.82	0.50	0.82	0.82
Kevlar 49/Epoxy	E = 76 GPa σ = 1380 MPa ε = 1.6%	0.59	1.06	0.59	0.59
Graphite/Epoxy	E = 160 GPa σ = 1725 MPa ε = 0.9%	0.28	1.51	0.28	0.28
Boron/Epoxy	E = 210 GPa σ = 1240 MPa ε =0.6%	0.21	3.15	0.21	0.21

* Values are representative averages without application of reduction coefficients for aging and environmental durability

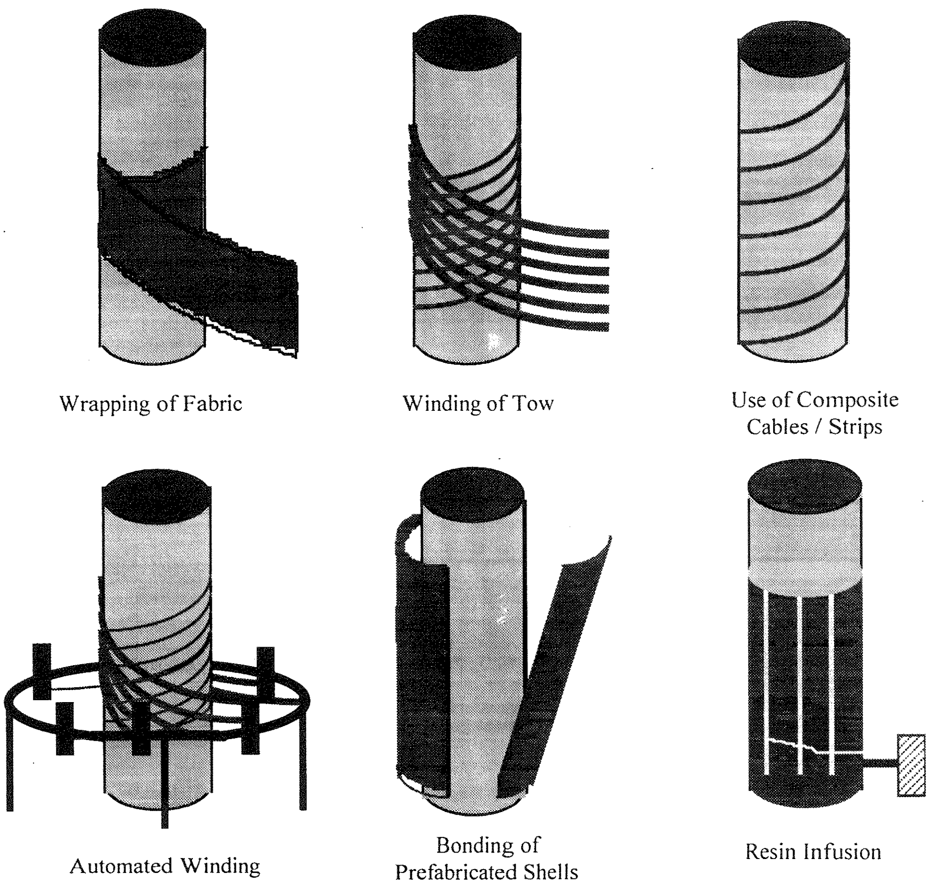
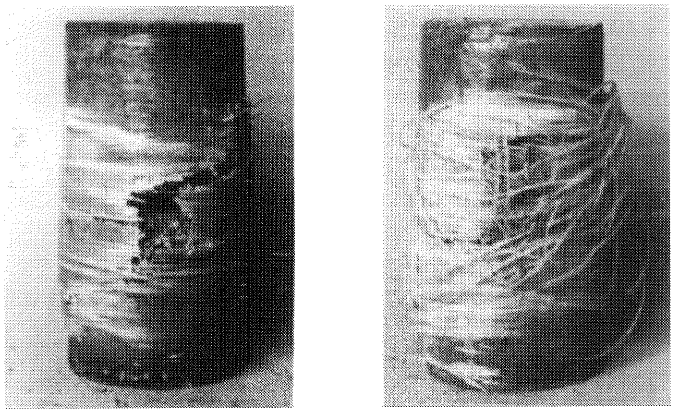


Fig. 1: Schematic of methods of seismic retrofit of columns using composites

Figure 1, have been developed, and can be differentiated into six basic types based on the form of material, process, or installation procedure used. The wet layup process is generally associated with manual application and the use of ambient cure, although it is possible to heat the system after application to achieve higher cure temperatures and hence higher glass transition temperatures. The process affords considerable flexibility of use especially in restricted spaces, but there are concerns related to the quality control of the resin mix, attainment of good wet-out of fibers with uniform resin impregnation without entrapment of excessive voids, good compaction of fibers without excessive wrinkling of the predominantly hoop directed fibers, control of cure kinetics and achievement of full cure, and aspects related to environmental durability during and after cure due to the use of an ambient cure process. In the case of wet-winding of tow or tape, the process may be automated, although resin impregnation is still through the use of a wet bath and/or spray, and many of the concerns are the same as those described for the wet layup process. The use of prepreg material generically uses an elevated cure, with the winding process for tow and tape being automated, and the fabric process being manual in terms of lay-down. Both these variants use an elevated cure and hence concerns related to Tg (glass transition temperature) are assuaged as long as appropriate fabrication techniques are followed and anhydride based systems are not used (due to the moisture sensitivity of these systems during cure). In the case of prefabricated shells, the sections are fabricated in a factory and then adhesively bonded in the field so as to form the jacket. This can be done using either two sections or a single section which is stretched apart so as to encapsulate the column. This process affords a high level of materials quality control due to controlled factory based fabrication of the shells. However, the efficiency and durability of the system rests on the ability of the adhesive to transfer load, and hence is dependent on the integrity of the bond which is constructed in the field and on the durability of the adhesive in a harsh and widely varying environment which could include excessive moisture (or immersion in water, in the case of a flood plain) and large temperature gradients. In the case of resin infusion, the dry fabric is applied manually and resin is then infused using vacuum with cure being under ambient conditions. FRP composite cables or prefabricated strips can also be helically wound around the column. In the latter case, aspects related to the appropriate use of an adhesive system must be considered, whereas the viability of end attachments or anchors becomes a critical concern in both cases. Irrespective of the method used, it is important to note that aspects related to material forms (tow, dry fabric, impregnated fabric etc.), processing (lay-up, cure, etc.), and location of fabrication (field versus prefabricated) will have an effect on the final performance and longevity of the material system in use.

This is a fiber dominated application, with the predominant role of the composite being to enable the application of constraint to the concrete core. The resin serves a very useful function beyond that of a matrix in acting as a protective layer for the fibers, both from environmentally induced and accidental impact induced damage. It should however be noted that the composite, even in the undamaged state, changes response to a certain degree with the environment. A classic example is that of increase in stiffness and in compression strength after exposure to subzero temperatures due to matrix hardening and stiffening (Karbhari and Pope, 1994; Karbhari and Eckel, 1994). Not only can this change the response of the entire system (stiffness changes can as high as 15-



(a) (b)

Fig. 2: Comparison of Failure Modes as a Consequence of Environmental Exposure to (a) Fresh Water Under Ambient Conditions, (b) 0° F (dry)

20%) but it also results in the introduction of new forms of damage and failure mechanisms. Figures 2a and b show the dramatic change in failure mode of a glass epoxy wrap after short-term exposure to sub-zero and fresh water (at ambient temperature) conditions. The tearing, inter-roving delamination and shredding of the hoop reinforcement in the former is traceable to the enhanced stiffness and hardening of the resin at sub-zero temperatures. Effects such as this, although not directly considered in design through the use of common structural equations, do need to be taken into account to ensure that changes in response or failure mode due to environmental exposure do not result in unexpected events. Again as is clear from the two figures, the changes in mode are a result of change in response at the resin and interphase level, rather than directly ascribable to changes in the fiber.

In designing with these materials for this application, it is important to note that the increase in stiffness of the column itself is not a goal of the retrofit. In fact this could be harmful vis-à-vis the response of the entire structural system. A common concern related to the use of fiber reinforced composites for seismic retrofit is the accurate determination of composite properties under loading conditions that replicate the actual situation of a confined column. Coupon level tension, flexure and shear tests which are routinely conducted to characterize composite properties, do not address this important aspect. In cases of circular columns, the composite is reinforced predominantly in the hoop direction with fibers arranged in the circumferential direction around the concrete core. This entails the formation of a composite that is curved rather than flat, and by definition incorporates stresses resulting from that curvature. Although standard tensile tests such defined by

ASTM D3039 could be used to determine performance levels as related to tensile strength, stiffness and strain-to-failure in the fiber direction these do not accurately reflect the state in the composite formed as a jacket. One way to determine properties which simulate those in a field wrap is to conduct a NOL ring or "burst" test, wherein a 508 mm (20 in.) diameter ring of the material in the configuration used in a jacket is placed in an apparatus and then hydraulically pressurized internally to simulate confinement and impart only circumferential stresses to the ring (Karbhari et al., 1997). An added advantage to such a test, beyond the determination of design properties, is the capability to test systems that are fabricated through the adhesive bonding of shell segments to form a jacket.

Whereas tensile, or other characterization level tests would not give a true indication of structural performance, and failure mode, the NOL ring test does, even replicating failure modes ranging from tensile failure of fibers in a hoop dominated prepreg tow based system, to an adhesive joint failure in the case of prefabricated jackets which are field bonded (Figure 3). Further study is required in this area to assess the effects of cyclic loading, and thermal cycling, keeping in mind that the concrete column serves as a heat sink, and that the adhesive can have a significantly different coefficient of thermal expansion than the composite or the concrete. This test can also be used to accurately assess the effect of environmental exposure on the behavior of the retrofit system itself, including that induced by premature softening or plasticization of the adhesive, if any. It should be noted that in some systems there is no bond between the composite and the concrete, whereas in others an adhesive bond does exist. Although the discussion

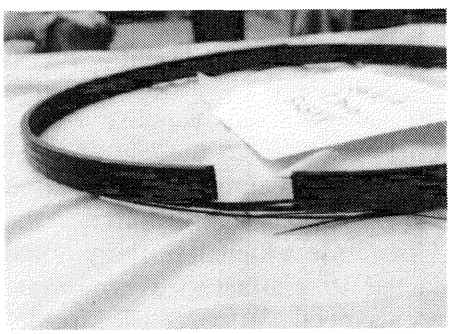


Fig. 3a: NOL Ring (Carbon/Epoxy Prepreg Tow) Showing Tensile Failure

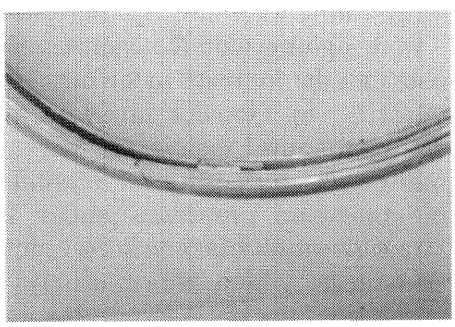


Fig. 3a: NOL Ring (Glass/Polyester) Showing Failure Along Adhesive Joints

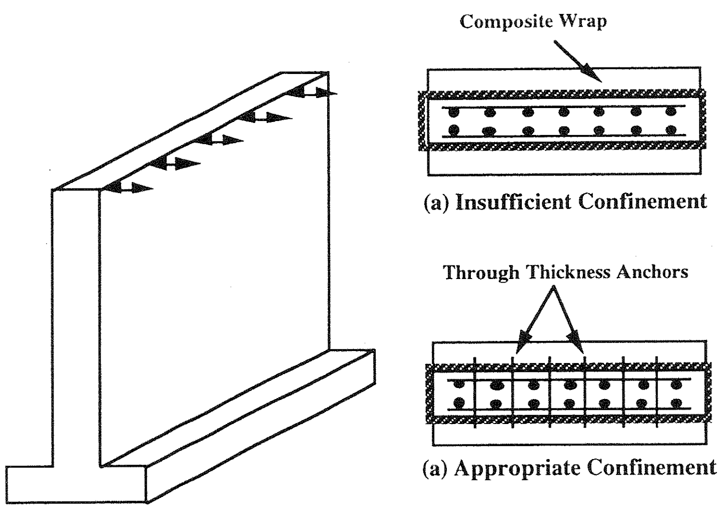


Fig 4: Design Detailing for the Seismic Retrofit of Large Aspect Ratio Rectangular Columns/Pier Walls

herein has focused on the retrofit of circular columns, there are a large number of non-circular cross-sections in need of retrofit. Significant challenges exist in confining large aspect ratio columns and pier walls, including those related to failure modes and fracture mechanisms when intermediate ties/bolts are used to decrease the active confining distance, such as in Figure 4. In the absence of the dowels/bolts/ties the jacket is not anchored and does not actually confine the material appropriately between the two shorter end.

3 Strengthening of Slabs

The application of composite materials to surfaces of beams and slabs in order to strengthen existing structures or to correct deficiencies in deteriorating structural components provides an attractive alternative to conventional measures (Meier, 1987; Meier et al., 1993) and significant research has been conducted in assessing the structural response of beams retrofitted with composite fabric and pultruded strips. Keeping in mind the differences in conventional steel reinforcement detailing and structural response between beams and slabs, it is noted that results derived from the application of composites to beams cannot be directly extrapolated to application of slabs especially as related to selection of the form and positioning of the external reinforcement (Karbhari and Seible, 1998). In general FRP composites can be applied in three ways as described in Table 2.

Table 2: Methods of Application of External Composite Reinforcement for Strengthening

Procedure	Description	Time
Adhesive Bonding	Composite strip/panel/plate is prefabricated and cured (using wet lay-up, pultrusion, or autoclave cure) and then bonded onto the concrete substrate using an adhesive under pressure	Very quick application
Wet Lay-up	Resin is applied to the concrete substrate and layers of fabric are then impregnated in place using rollers and/or squeegees. The composite and bond are formed at the same time.	Slower and needs more set-up
Resin Infusion	Reinforcing fabric is placed over the area under consideration and the entire area is encapsulated in a vacuum bag. resin is infused into the assembly under vacuum with compaction taking place under vacuum pressure. Unlike the wet lay-up process this is a closed process. In a variant the outer layer of fabric in contact with the vacuum bag is partially cured prior to placement in order to assure a good surface.	Far slower with significant setup time needed

Irrespective of the method of application, it is important to realize that the efficacy of the method depends primarily on the appropriate selection of the composite material, and the integrity and efficiency of the bond between the concrete surface and the composite. Beyond the actual failure of the retrofit system due to severe deterioration of the adhesive, resin and/or composite (which should only occur through a serious error in materials selection, processing scheme, or design), failure due to combined materials-structural response can be generally associated with one or a combination of following modes: (a) Tensile fracture of the composite due to excessive strain demand in the maximum moment zone; (b) Peel failure from the reinforcement end leading to a shear-tension failure resulting in the propagation of a horizontal crack in the concrete and which results in separation of the concrete cover; (c) Interfacial failure or debonding at the concrete-adhesive interface, which is generally initiated at a flexural or shear crack; (d) Cohesive failure in the adhesive layer resulting in pseudo-plastic response in some cases; (e) Development of an alternating crack path between the two interfaces (concrete-adhesive and adhesive-composite). and (f) Shear-tension failure in the concrete section outside the area reinforced by the composite. Finite element analyses for the investigation of the development of some of these mechanisms is given in (Xie and Karbhari, 1997) The first two mechanisms are symptomatic of good overall structural response since they occur after large deflection of the member, accompanied by yielding of the steel, and use of significant (if not complete) portion of the composites capacity. The mechanisms of shear-tension failure at the concrete-composite interface

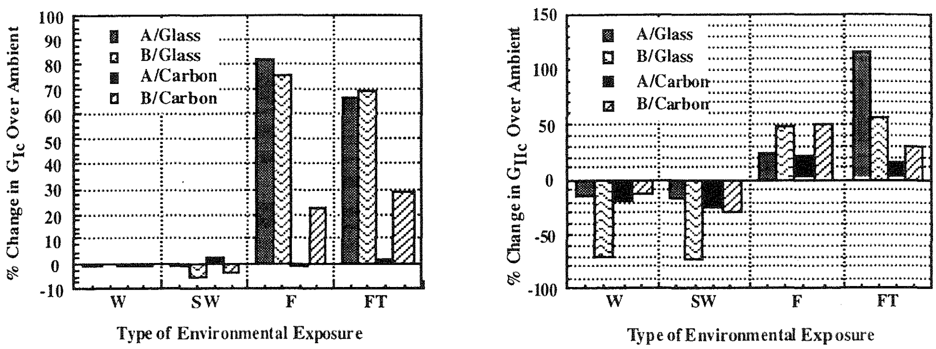


Fig. 5: Effect of Environmental Exposure Conditions on Critical Energy Release Rates Derived From Peel Tests (W: Water, SW: Salt Water, F: Frozen Conditions, -15.5°C, FT: Freeze Thaw)

at the end of the composite lead to separation of the cover concrete, and that of debonding at the concrete-composite interface are brittle mechanisms that occur at lower load levels and are symptomatic of bond degradation, deterioration of concrete cover material due to entrapment, and/or stress mismatch. Figure 5 shows the results of the use of a modified peel tests to determine the effect of environmental exposures on energy release rates of four different composite systems used in strengthening (A and B denote two different resin types). As can be seen there is a significant effect of environmental exposure especially as related to the effects of stiffening due to sub-zero conditioning. These aspects need to be further evaluated using a fracture mechanics approach so as to understand the role played by adhesion and bonding between the two dissimilar surfaces (concrete and composite).

4 Conclusions

There is an increasing need to develop an understanding of materials and design considerations in the use of composites for the rehabilitation of concrete components. Although composite layers can be easily bonded onto concrete and can be made to closely follow the contours of the structure, care has to be taken to ensure that good detailing practice is followed to ensure against premature failure. The development of fracture mechanics based design principles in conjunction with criteria for the selection of materials (fiber, resin, adhesive) and their form is seen to be a critically needed step towards the efficient and safe use of these techniques.

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