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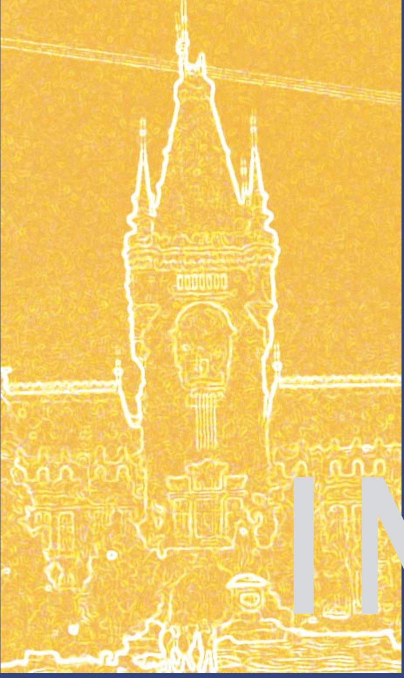

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Advanced polymeric composites and strengthening concrete structural members

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Summary

The use of fiber reinforced polymer (FRP) composites for structural strengthnening of reinforced concrete (RC) load-bearing elements has become a common practice in the last decades. However, the efficient of these new materials and systems must be preceeded by a carefull evaluation of their potential and constrains. The paper presents the main strengthening solutions of the RC elements made of concrete and their critical evaluation based on the existing experience in the area of structural rehabilitation.

KEYWORDS: seismic retrofit, wet lay-up, epoxy resins, glass and carbon fibres

1. INTRODUCTION

Over the last three decades structural strengthening of concrete structures has become an important issue due to ageing of infrastructure and the need for upgrading to fulfill more stringent design requirements. Also the seismic retrofit has become more important mainly in seismic active areas.

The use of fibre reinforced polymer (FRP) composites in strengthening solutions has become a viable alternative to some of the existing traditional methods due to some advantages such their features in terms of strength, lightness, corrosion resistance and ease of application.

Such techniques are also most attractive for their fast execution and low labour costs. FRP composite products for structural strengthening are available in the form of prefabricated strips, precured shapes or uncured sheets applied through wet lay-up procedure.

Prefabricated plates are typically 0.5-1.5 mm thick and 50-200 mm wide, and they are made of unidirectional fibres (glass, carbon, aramid) in a thermosetting matrix (epoxy, polyester, vinylester). Uncured sheets typically have a nominal thickness of less than 1 mm, are made of fibres (unidirectional or bidirectional) preimpregnated or in situ impregnated with resins. Bonding is achieved with epoxy adhesives when prefabricated composite elements are utilized and with impregnating resins in the latter case. Composites were first applied as confining reinforcement of reinforced concrete (RC) columns [1], and as flexural strengthening materials for RC bridge girders [2].

Since the first applications the developments have been tremendous and the range of applications has expanded to timber, masonry and metallic materials. The number of applications involving FRP composites as strengthening materials for RC elements and structures has expanded from a few, about 15 years ago to more than ten thousand nowadays.

2. STRENGTHENING SOLUTIONS OF RC MEMBERS

2.1 Traditional methods

Strengthening solutions of RC members can range from repair of damaged members so that their original load-carrying capacity is restored, to adding elements to increase their strength. All solutions are project-specific to a certain application but some general approaches are commonly utilized. The most traditional techniques for strengthening the RC structures are as follows [3]:

- Increase the reinforced concrete cross-section
- Add prestressing to relieve the dead load
- Use plate bonding to enhance tensile reinforcement of the RC elements
- Add confining elements to improve behaviour of the concrete in the compression members
- Shear strengthening by installing external straps

2.2 FRP composite based solutions

Strengthening of old and/or deteriorated reinforced concrete (RC) members is often required due to the following causes [4,5]:

-*The inadequacy of longitudinal reinforcement* in beams and columns, leading to flexural failure. In such cases the bending capacity of concrete elements can be increased through the use of externally bonded FRP plates, strips or fabrics. Alternatively near-surface mounted strips or rods with the fibre direction parallel to the member axis can be utilized.

-*The inadequacy of transverse reinforcement*, which may have as effect brittle shear failure in structural members like columns, beams, shear walls and beam-column joints. The shear capacity of concrete members can be enhanced by providing externally bonded FRP with the fibres oriented in the transverse direction to the member axis direction, in the case of columns and beams, or in the direction of both the column and the beam direction in the case of beam-column joints.

-Poor detailing in the regions of flexural plastic hinges where the flexural cracking may be followed by cover concrete spalling, failure of transverse steel reinforcement, and buckling of longitudinal steel reinforcement or compressive crushing of concrete. This mode of failure is usually accompanied by large inelastic flexural deformation. By adding confinement in the form of FRP jackets with fibres placed along the column perimeter, the spalling of cover concrete is prevented and the buckling of the longitudinal steel bars is restrained. In this way more ductile responses can be developed and larger inelastic deformations can be sustained.

-Poor detailing in lap splices. This mode occurs in columns in which the longitudinal steel reinforcement is lap spliced in the maximum bending moment regions near the column ends. Debonding may occur once vertical cracks develop in the cover concrete and progresses with cover spalling. By increasing the lap confinement with fibres along the column perimeter the flexural strength degradation can be prevented or limited.

The use of FRP reinforcement cannot modify the stiffness characteristics of existing RC elements; hence the FRP strengthening technique is not applicable if the structural intervention is aiming at increasing stiffness rather than strength or ductility [5].

2.2.1 Flexural strengthening of beams

The need for methods of repair and strengthening of RC beams and girders has been imposed by: degradation due to corrosion of steel reinforcement, cracking of concrete due to excessive carbonation, freeze-thaw action, spalling of concrete cover, effects of alkali-silica reactions and changing in loading patterns [6]. In case of bridges the need for increasing their load carrying capacities requires the adoption of a cost-effective technology that will not distress the traffic significantly.

In buildings the materials deterioration and changing needs for building occupancy imposes, in many cases, the strengthening of existing beams. One of the conventional methods for external strengthening implies the addition of adhesive-bonded steel plates on the tension side of the RC beams. The use of epoxy-bonded steel plates is very frequent in Europe and the United States but it suffers from a number of disadvantages:

Steel plates are heavy and difficult to transport, handle and install; the length of individual steel plates is restricted to 8-10m to enable handling and even at these

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lengths it may be difficult to erect them due to pre-existing service facilities; durability and corrosion effects remain uncertain; contaminants on structural members prior to bonding; surface preparation including the priming systems; steel plate thickness at least 5 mm to prevent distortion during blasting operation; complex profiles are difficult to be shaped with steel plates; expensive false work is required to maintain steel plates in position during bonding.

Composites fabricated either through wet processes on-site or prefabricated in plates, Figure1, and then adhesively bonded to the concrete surface provide an efficient means of strengthening, that can be carried out with no or little disruption in use. The efficacy of the method depends mainly on the appropriate selection of the composite material and on the efficiency and integrity of the bond between the composite and the concrete surface.

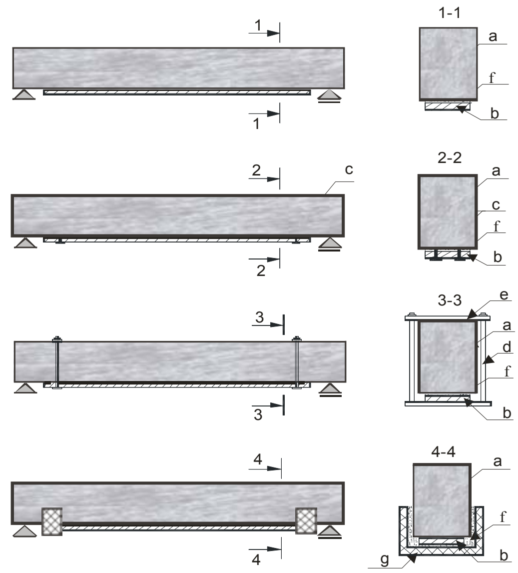

Figure 1. Strengthening of RC beams with FRP soffit plates. a- concrete; b-FRP plate; c-anchor bolts; d, e - elements of the metallic jig; f - adhesive layer

2.2.2 Shear strengthening of beams

When a RC beam is deficient in shear, or when its shear capacity is less than the flexural capacity after flexural strengthening, the shear strengthening of the respective beam has to be considered. It has been realized that the FRP bonded to the soffit of a RC beam does not modify significantly the shear behaviour from that of the unstrengthened beams [7,8].

Therefore, the influence of FRP strips bonded to the soffit for flexural strengthening may be ignored in predicting the shear strength of the beam. Various

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bonding schemes of FRP strips have been utilized to improve the shear capacity of reinforced concrete beams. The shear effect of FRP external reinforcement is maximized when the fibre direction coincides to that of maximum principal tensile stress.

For the most common case of structural members subjected to transverse loads the maximum principal stress trajectories in the shear-critical zones form an angle with the member axis which may be taken about 45°. However, sometimes it is more practical to attach the external FRP reinforcement with the principal fibre direction, perpendicular to the axis direction, Figure 2, [9].

Because FRPs are strong in the direction of fibres only their orientation is recommended to control the shear cracks best. Shear forces in a beam may be reversed under reversed cyclic loading and fibres may be thus arranged at two different directions to satisfy the requirement of shear strengthening in both directions.

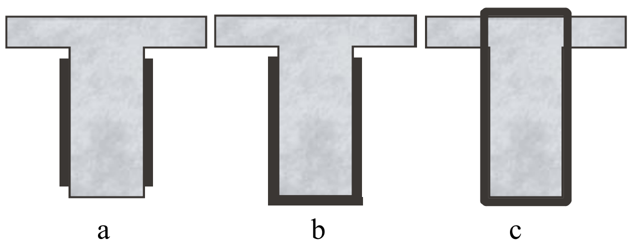

Figure 2. Shear strengthening schemes with FRP composites. a - FRP bonded to the web sides only; b-U jacketing; c-complete wrapping

2.2.3 Strengthening of RC plates

When the RC plates are simply supported the one-way plates are strengthened by bonding FRP strips to the soffit along the required direction, Figure 3. For two-way plates strengthening must be applied for both directions, by bonding FRP strips in both directions, Figure 4.

Figure 3. FRP strengthening of one-way simply supported plate:

a- elevation; b- cross section

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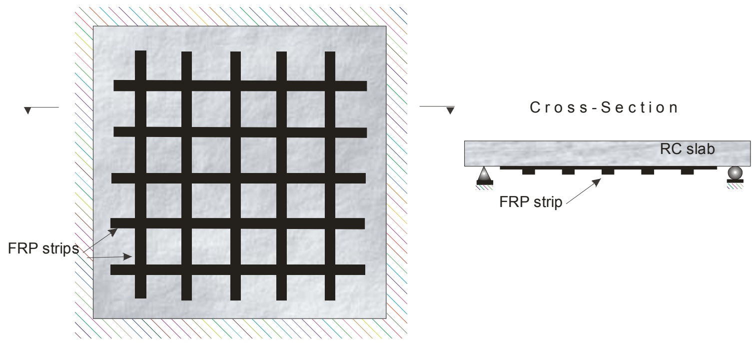

a. b.

Figure 4. FRP strengthening of a two-way slab:

a- slab soffit; b- cross section

The possible collapse mechanism of a two-way slab suggests that the strengthening of such a plate can be concentrated in the central region, Figure 4, and the FRP strips can be terminated far away from the edges [4]. The load capacity of such strengthened plates can be predicted by a yield line analysis, as the part of the slab without bonded FRP strips has enough ductility for the formation of yield lines.

2.2.4 Strengthening of RC columns

Conventional strengthening measures for RC columns range from the external confinement of the core by heavily reinforced external concrete sections to the use of steel cables wound helically around the existing column at close spacing that are then covered by concrete and the use of steel jackets welded together in the field confining the existing columns [10].

Some of these methods are effective but they have some disadvantages: they are time consuming and labour intensive; can cause significant interruption of the structure functioning due to access and space requirements for heavy equipment; rely on field welding, the quality of which is often questionable; susceptible to degradation due to corrosion; introduce changes in column stiffness, influencing the seismic force levels.

The strengthening of existing RC columns using steel or FRP jacketing is based on a well established fact that lateral confinement of concrete can substantially enhance its axial compressive strength and ductility [11]. The most common form of FRP column strengthening involves the external wrapping of FRP straps. The use of FRP composites provides a means for confinement without the increase in stiffness (when only hoop reinforcing fibres are utilized), enables rapid fabrication of cost effective and durable jackets, with little or no traffic disruption in most cases.

In FRP-confined concrete subjected to axial compression, the FRP jackets are loaded mainly in hoop tension while the concrete is subjected to tri-axial compression, so that both materials are used to their best advantages. As a result of the confinement, both the strength and the ultimate strain of concrete can be enhanced, while the tensile strength of FRP can be effectively utilized. Instead of the brittle behaviour exhibited by both materials, FRP-confined concrete possesses an enhanced ductility.

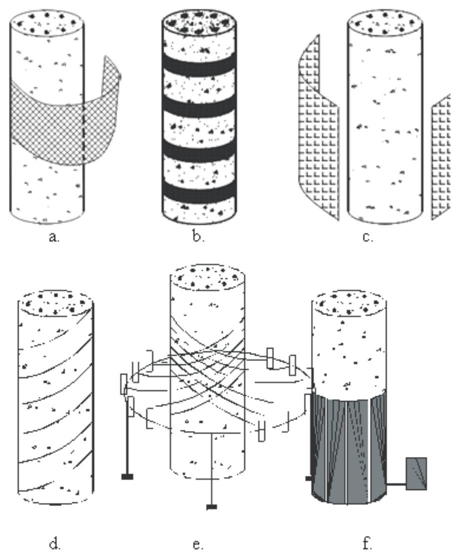

Figure 5. Methods of FRP strengthening for RC columns:

a. wrapping of fabric; b. partially wrapping with strips; c. prefabricated jackets
d. spiral rings; e. automated winding; f. resin infusion.

For FRP wrapped, axially loaded columns the design philosophy relies on the wrap to carry tensile forces around the perimeter of the column as a result of lateral expansion of the underlying column when loaded axially in compression. Constraining the lateral expansion of the column confines the concrete and, consequently increases its axial compressive capacity.

It should be underlined that passive confinement of this type requires significant lateral expansion of the concrete before the FRP wrap is loaded and confinement is initiated. In case of columns rectangular or square in cross section the confinement is effective at the column corners only with negligible resistance to lateral expansion being provided along the flat column sides.

A number of different methods (based on form of jacketing material or fabrication process) have been tested at large or full-scale many of which are now used commercially all over the world. A suitable classification of FRP composite jackets is given in, Figure 5 [12, 13].

3. ADVANTAGES OF FRP COMPOSITE STRENGTHENING

- FRP composite have higher ultimate strength and lower density than steel, although the strength to density ratio much higher than steel plate can not be generally fully utilized.
- The lower weight of FRP materials makes handling and installation significantly easier than in case of steel plates. Composite plates applied to the soffit of bridge girders do not require heave lifting equipment. When FRP plates are applied pressure is exerted to their outer surface to remove adhesive in excess and entrapped air. They can practically be left unsupported. In general there is no need to use bolts for FRP plate fixing and this avoids the risk of damaging the existing steel reinforcing bars.
- FRP composite sheets are available in long lengths (compared to steel plates generally limited to 6m) and their installation is much simpler: laps and joints are not required; the material can accommodate some irregularities; the thin FRP plates and sheets can follow a slightly curved shape without prebending; overlapping required when strengthening plates in two directions is not a problem because the composite products are thin.
- The energy required to produce FRP materials is less than for traditional materials fact that leads to sustainable solutions with minimum impact on the environment.
- The combination of all these advantages leads to simpler and quicker strengthening processes than when steel products are utilized. This is especially important for bridges because of the high costs of circulation lanes closures.

4. DISADVANTAGES OF FRP COMPOSITE STRENGTHENING

- The most important disadvantage of FRP externally strengthened structures seems to be the risk of accidental damage, vandalism or fire occurrence. However strengthening using FRP plates affected by the composite products

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damage can only reduce the overall factor of safety and it is unlikely to lead to collapse.

- New unfamiliar failure mechanisms are possible particularly in FRP plate bonding and specialist expertise should be provided [13].
- Workmanship skill and quality are critical to the success of applying an FRP composite strengthening solutions. Therefore certification schemes for workers and supervisors are needed to be developed prior to application of these procedures especially at important works.
- It is difficult to control the quality of the adhesive layer or the presence of the entrapped air than can affect the bond between FRP plate and the concrete surface.
- Experience on the long-term properties of FRP strengthening schemes is limited, and this can be a disadvantage for structural members requiring a very long design life.
- The relatively high initial cost of the FRP materials and products used in the strengthening schemes is a perceived disadvantage but the comparisons should be made on the complete strengthening procedure and life-cycle assessment.
- Many potential clients may claim the lack of experience of most operators in the construction market but this can be overcome by choosing qualified designers and contractors.

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Increasing the Security in Exploitation of Steel Structures by Correct Managing the Corrosion Phenomenon

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Summary

The sustainable development of the modern society involves an extensive knowledge of the environmental conditions - of all the factors that produce decay or, on the contrary, improve its state. An increase of the security during the service life of the steel structures is imposed by all the measures taken during the process of corrosion management.

The corrosion phenomenon is put into evidence by the irrevocable distruction of metallic elements and its particular nature determined the development of new detailed monitoring techniques and procedures that led to its better understanding by the specialists working in this particular science field.

The complexity of its manifestation, the various factors that influence the corrosion patterns make this phenomenon impossible to be described by general features. For this reason, the solutions adopted for a best corrosion protection must be the result of well organised systematic approaches and a careful planning of the corrosion management .

Keywords: sustainable development, metallic corrosion, steel structures, corrosion management

1. SUSTAINABLE DEVELOPMENT CONCEPT IN THE DOMAIN OF METALLIC CONSTRUCTIONS

The modern concept regarding the quality and performances of the constructions includes the basic criteria of sustainability, which is essential for the steel structures exploited in particular aggressive environmental conditions. This concept implies not only reaching a prior degree of technical characteristics but also maintaining them unaltered for their entire expected period of normal exploitation of the construction.

The promotion of this concept is based on extensive knowledge of the real state of the environment and also, of the factors that may cause degradation or, on the contrary, an increase of its general qualities. For this reason it is very important to study the ways of affecting this environment by the human presence, whether it is an alteration or an increase of these qualities.

The analysis of causes and consequences of the human presence integrated in environment is the principal objectives of study in the concept of sustainable development and in this respect, the links between the human society and the natural conditions must be very well understood in order to elaborate specific techniques to foresee and evaluate the impact of entropic elements at the environmental level. This major goal may be reached by developing and using new techniques of analysis and prognoses for an accurate evaluation and monitoring of the impact of the human communities on the natural global eco-systems.

2. NEGATIVE EFFECTS OF THE CORROSION OF METALS

Corrosion consists in destructive effects of an aggressive environment upon the metallic elements. Its economical consequences are negative to extreme due to the massive lost of the material that insured the initial capacities of resistance. The diminished resistance affects the security of normal exploitation of the constructions and also a dramatic reduction of their service life. Increased costs of maintenance and sometimes pollution in general and in particular, the impurities of the finite products are second order effects of the corrosion presence in the elements of construction.

We associate the corrosion phenomenon with the concept of a sustainable development in different areas of human activities and the implications of its presence act directly upon the various measures of protection, mostly all the time being the result of the compromise between many technical, economical and ecological criteria.

It is a common aspect to identify corrosion with one of the most serious threats in the economy of the modern society, increasing the costs of maintenance and development and generally being the cause of an important annual lost of material, the equivalent of hundreds of billions dollars.

Since the first significant report of Uhlig in 1949, according to which the costs of corrosion to nations is indeed great [1], numerous studies dedicated to this phenomenon were in charge of several countries including, the Unites States, the United Kingdom, Japan, Australia, Kuwait, Germany, Finland, Sweden, India and China.

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The studies have ranged from formal and extensive efforts to informal and modest efforts. The common finding of these studies was that the annual corrosion costs ranged from approximately 1 to 5 percent of the Gross National Product (GNP) of each nation and further on, the conclusion of all subsequent studies has been that corrosion represents a constant charge to nations' Gross National Product.

Several studies separated the total corrosion costs into two parts:

• the portion of the total corrosion cost that could be avoided if better corrosion control practices were used;
• the situations when savings require new and advanced technology (currently unavoidable costs).

Estimates of avoidable corrosion costs varied widely with a range from 10% to 40% of the total cost. Most of the studies allocated corrosion costs to industrial sectors or to categories of corrosion control products and services. New technologies to prevent corrosion continue to be developed and cost-based corrosion management techniques are available to further lower corrosion costs. However, cost-effective methods are not always implemented.

Corrosion damage can sometimes be greatly exaggerated by the circumstances. While most of the accidents due to failed components that corrode have gone non-public for reasons of liability or simply because the evidence disappeared in the catastrophic event, others have made the headlines [2].

A decreasing order of the frequency of appearance identifies the causes of corrosion damage as an unadequate anticorrosion protection method, the unexpected exploitation conditions and the lack of an efficient control and monitoring system. Failure is also caused by a bad choose of the materials of construction, of the steel sections and their connections, these being summerized as faults of the design process. To these may be added errors of manipulation at the building site, the lack of knowledge of the risks involved by different corrosion levels, the contamination of the products and also the malfunction of the control and monitoring equipments.

The depth of the analysis into the "roots" of the failure is the key to an "accurately unearthing" all of the failure sources. Looking at machinery failures one finds that there are:

- physical roots (the physical reasons why the parts failed);
- human roots (the human errors of omission or commission that resulted in the physical roots);
- latent roots (Management System Weaknesses). The deficiencies in the management systems or the management approaches that allow the human errors to continue unchecked.

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In table 1 the principal primary mechanisms of the damages from 131 analyses are presented synthetically [5]. After the study of these priorities of the failure mechanisms, the competence and responsibilities of these situations in U.S.A. were identified [3]. This data set indicates that only 8% of corrosion failures are unforeseeable; in other words 92% of the corrosion failures could be preventable. The small percentage of corrosion damage attributed to a lack of human performance by the Hoar report, the Battelle studies and many others, i. e. roughly 30-40% of total corrosion damage, would be overly optimistic.

Table 1. Primary mechanisms of failure and the causes of destruction by corrosion

Primary mechanisms of failure by corrosion		Causes of destruction by corrosion in U.S.A.	
23 Corrosion	18%	Lack of proving: new design, material or process	36%
57 Fatigue	44%	Lack of, or wrong specifications	16%
15 Wear	11%	Bad inspection	10%
17 Corrosion Fatigue	13%	Human error	12%
19 Overload	15%	Poor planning and coordination	14%
		Other	4%
		Unforeseeable	8%

Considering the corrosion types of most of the common damages, the pie chart in fig. 1 summarizes the findings of 363 corrosion failure cases investigated in a major chemical processing company [4]. The importance of pitting comes second (22%) after general corrosion and before stress corrosion cracking (SCC) which is, by the way, often initiated by pitting. Crevice corrosion comes fourth at 12%.

3. CORROSION MANAGEMENT

While corrosion will always remain a threat, there are many barriers that can be deployed to protect a system against the environment corrosion severity.

The *first barrier* is awareness and the tool to create awareness is through education and training. The *second barrier* is to do it right in the first place. Metals are naturally more stable in their non-metal states such as oxides and sulphides. Given a chance they will revert back spontaneously to the comfortable states. Designers often forget this basic law of nature. The *third barrier* is through management. Corrosion can be managed if the right decisions are based from the start on the full life cycle of a system. Buying systems and components without considerations for subsequent maintenance is flawed and can be very expensive.

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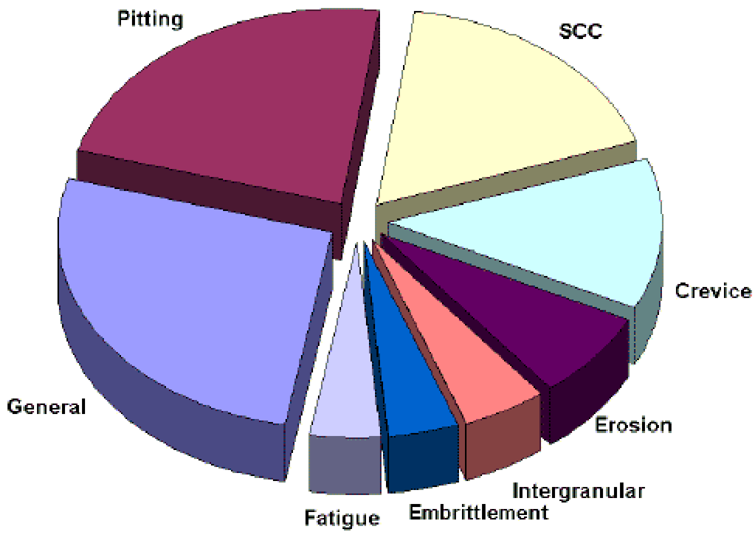

Figure 1. Types of corrosion that affects the chemical industrial field

"Corrosion management is that part of the overall management system, which is concerned with the development, implementation, review and maintenance of the corrosion policy." [2]. Corrosion management includes all activities throughout the lifetime of the structure that are performed to mitigate corrosion, to repair corrosion induced damage, and to replace the structure, which has become unusable as a result of corrosion. In general, maintenance is defined as an activity that maintains the level of service of a structure or facility.

Repair activities restore the damaged structure to its original or required service levels, but do not eliminate the causes of corrosion. Rehabilitation activities restore the damaged structure to its original or required service level and correct the deficiency that resulted in corrosion deterioration. The repair and rehabilitation activities are performed at different times throughout the lifetime of the structure. Maintenance is considered a regular activity, characterized by an annual cost. Inspections are scheduled periodic activities, and repair is performed on an as-needed basis. Repair can involve the replacement of parts, but not the replacement of the basic structure. Rehabilitation of structures such as bridges is usually done only once or twice during the lifetime of the structure, generally at a high cost.

The complexity of engineering systems is growing steadily with the introduction of advanced materials and modern protective methods. This increasing technical complexity is paralleled by an increasing awareness of the risks, hazards and liabilities related to the operation of engineering systems. The increasing cost to

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replace equipment is forcing people and organizations to extend the useful life of their systems.

Identification of hazards, assessment of risks and agreement on planned activities is a fundamental requirement of the management process.

Even at the most basic level, there are multiple interactions between defects (departure of a characteristic of a system from requirements), faults (inability of s system to perform a required function) and the failure of a system (termination of the ability of a system to perform a required function).

The prediction of damage caused by environmental factors remains a serious challenge during the handling of real life problems or the training of adequate personnel. Mechanical forces, which have normally little effect on the general corrosion of metals, can act in synergy with operational environments to cause the most sudden failures by localized mechanisms.

To determine the probability of a failure, two fundamental issues must be considered:

- what are the specific forms of corrosion and their rates,
- what is the possible effectiveness of inspection.

The input of corrosion experts is required to identify the relevant forms of corrosion in a given situation and to determine the key variables affecting the propagation rate. It is also important to realize that full consensus and supporting data on the variables involved is highly unlikely in real-life complex systems and that simplification will often be necessary.

The evolution of the corrosion process characterised by the corrosion rate marks the extense of the period of service in normal conditions of the metallic element as part of the construction. On the other hand, the measurements of the corrosion effects and the necessary remedies of the corrosion proces inits full development are actions that imply important costs. For this reason oly, the monitoring of the corrosion phenomenon is important, the specific techniques having as a result:

- a precocious detection of the development of the conditions of a further damaging process;
- the indication of the corelation between the modification of the parameters of the process and the effect upon the corrosion status of the system;
- diagnosis of a particular corrosion situation, the identification of its causes and the parameters that determine the evolution of the corrosion (the corrosion rate);
- the evaluation of the efficacy of the program of control/monitoring and preventing of the corrosion;
- providing of the necessary information of the stages of evolution of the corrosion for a better management of the phenomenon.

The last mentioned elements are the proof that corrosion is indeed a complex phenomenon and its multiple various factors sometimes lead to specific unavoidable manifestations. The solutions must be the result of a systematic approach.

The current study showed that technological changes have provided many new ways to prevent corrosion, and the improved use of available corrosion management techniques. However, better corrosion management can be achieved using preventive strategies in non-technical and technical areas. These preventive strategies include:

- increase awareness of large corrosion costs and potential savings,
- change the misconception that nothing can be done about corrosion,
- change policies, regulations, standards, and management practices to increase corrosion saving through sound corrosion management,
- improve education and training of staff in recognition of corrosion control,
- advance design practices for better corrosion management,
- advance life prediction and performance assessment methods.
- advance corrosion technology through research, development, and implementation.

There are many different ways the above issues can be achieved. This will be dependent on the size of the organization and the extent or otherwise that various duties and responsibilities are contracted or sub-contracted out to third party organizations. In fig. 2 a corrosion management flow chart is presented.

Planning and implementation of the corrosion management must eliminate all the damages or, at least must reduce at minimum their risks.

Planning includes: the identification of corrosion threats and consequences; ranking of systems and components in order of corrosion risk; selection of appropriate mitigation and management activities; scheduling of tasks.

Implementation ensures that actions identified in the planning stage are carried out as required and includes: translation of the plan into a detailed set of work packs; identification of the locations for monitoring and inspection activities; procedures for execution monitoring and inspection activities; development of acceptance criteria; development of performance measures; definition of the reporting routes; data gathering and management; analysis of data; reporting; corrective action or application of corrosion control measures.

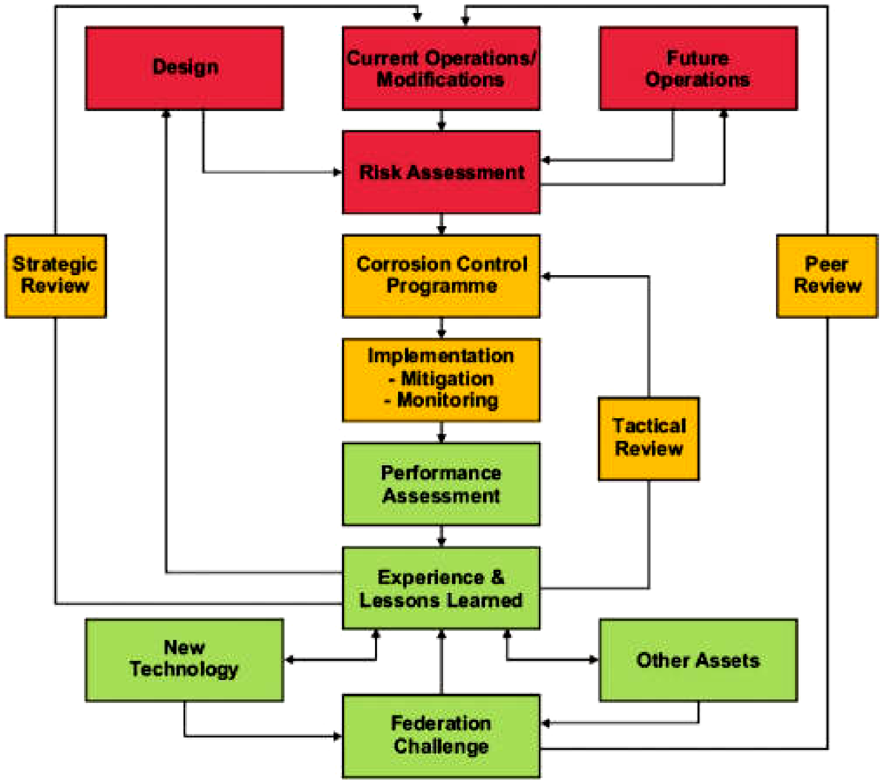

Figure 2. Example of corrosion management system [2], [5]

All organizations should have in place policies and strategies that deal with hazards and risks associated with safety, health and environmental concerns. Thus, although many companies may not have a stated corrosion policy, all accept the inherent concept of good corrosion management practice is implied and is incorporated into their planning process.

Development of strategies for corrosion management involves:

i) Overall management of corrosion risks: ensuring responsibility for corrosion management resides with a named individual whose authority should be equal to his responsibility; ensuring roles and responsibilities match the required competency; integrating corrosion management with safety and asset management and to inspection, maintenance and operations strategies; ensuring that risk assessment procedures remain live and are updated on a regular basis; providing an auditable trail for corrosion risk/criticality assessments; ensuring feed back from field experience into new designs and particularly that adequate corrosion input occurs at the concept stage.

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ii) Effective deployment of human resources: ensuring that adequate resources are available; ensuring technical and managerial competence, particularly where multi-skill manning is involved corrosion issues are delegated and become the responsibility of a non-specialist; involving all appropriate team members in sharing of information; evolving a proactive culture.

iii) Development of appropriate organizational structures: ensuring key information gets to the right people; using appropriate information control systems.

iv) Systems to meet changing situations: ensuring process fluids are monitored to identify changes of the corrosion process; updating and auditing all systems when implementing organizational changes; providing benchmarks and audits from which to develop future strategies; developing opportunity based inspection procedures.

The effectiveness of any policy depends on the leadership, commitment and involvement of managers and senior staff.

For organizing corrosion management the four "Cs" of a positive culture are: control, communication, competence, co-operation. Consideration of these four Cs is vital, particularly for management of complex multi-disciplinary areas, like corrosion management, which may well involve engineers that are not specialized in this respect.

4. CONCLUSIONS

In the present, corrosion phenomenon is better understood but in the same time the destruction of metals and the lost of material are a common presence in every domain. That is why new advanced techniques and methods of the control of this phenomenon are a continuous necessity.

The increasing quality of the materials used in the metallic constructions (mostly steel and aluminium), the new and notable technologies and products with higher resistance in aggressive environmental conditions challenges day by day the continuous evolution of the complex parameters of this aggressiveness.

A competition is born between corrosion and its remedies. As a direct implication, the solutions of protection tend to become more specific, directly used and easier to apply. Choosing certain specific systems of protection is the decision of personnel with high training and experience in this field.

Planning and management of the corrosion status must insure the elimination of the failure of materials for the life time of the construction and at least, must reduce to minimum the risks involved for the human occupancy and the costs of the accidental situations.

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An efficient management of the corrosion may be concieved by using strategies of adequate preventing methods and this is the responsability of the engineer specialised in corrosion.

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Particularities of FRP structural rehabilitation of concrete columns in frames

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Summary

Columns, in general, and reinforced concrete (RC) columns, in particular, are barely used as individual elements. In most of the structures, columns are but a part of the designing problem. The complex state of combined internal efforts makes the design of structural columns a very laborious task for the engineers.

When rehabilitation interventions are required, the problem becomes even more difficult. Lately, the use of Fibre Reinforced Polymer (FRP) composite materials in retrofitting the columns have shown to significantly improve the performance of RC columns as parts of frames.

The most usual problems related to the topic are the insufficient lap lengths in reinforcement splices, spalling of concrete resulting in premature loss of anchorage of the reinforcement bars and possible sudden/brittle failure mechanisms, insufficient transversal reinforcement leading to poor resistance in shear.

The present paper tries to point out the main aspects related to columns behaviors in shear, to make a comparative discussion of existing models for columns in shear and testing procedures. The principal methods of enhancing the shear strength of structural columns using FRP composite materials are also to be presented.

KEYWORDS: structural reinforced concrete columns; rehabilitation; shear resistance; fibre-reinforced polymers

1. INTRODUCTION

As they play the main role in undertaking lateral loads and are the principal resisting elements of RC structures, the RC columns are the most likely to fail in case of large loads acting transversely to their longitudinal axis. Such loads act upon the columns when earthquakes occur. Therefore, when speaking about columns as parts of frames, the main problems are related to preventing from premature failure of columns in case of earthquakes [1]. Further on, we may state

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that a good approach in seismic retrofit of structures should be focused on the retrofitting of columns.

The need for retrofit procedures may arise from various causes; yet, the most important may be considered the fact that relatively old structures do not meet anymore the present design philosophies.

The experience of last severe earthquakes, resulting in disastrous damages to a large number of buildings (e.g. Whittier Narrows 1987, Loma Prieta 1989, Northridge 1994, and Kobe 1995) made clear the necessity of a different designing philosophy concerning the seismic design of buildings. Changes concerning this aspect have been performed in most of the countries that have to deal with this problem.

2. TYPICAL RC COLUMNS FAILURE MODES UNDER SEISMIC LOADS

RC columns have to undertake a combination of lateral cycling loads and existing axial loads when earthquakes occur. Lack of sufficient shear, flexural strength, or ductility may lead to failure (rather brittle in most of the cases) of columns. There were established three typical modes of failure in case of RC columns when subjected to seismic loads: (1) shear failure; (2) failure of confinement in flexural plastic hinge regions; (3) lap splice failure of the longitudinal steel reinforcement.

2.1 Shear failure

Probably the most dangerous failure mode, the shear failure starts with diagonal concrete cracking, followed by a rapid failure or opening of transverse reinforcement. The successive buckling of longitudinal steel reinforcement results in a sudden, explosive failure of the column. (Figure 1, a))

Insufficient transverse reinforcement, improper detailing or bad anchorages of existing transverse steel reinforcement are common causes leading to shear failure. Problems concerning the improper detailing include steel hoops insufficiently lap spliced, insufficient anchorage lengths of hoops in the concrete core.

Columns that are identified as having such problems must be strengthened in shear when retrofitting is discussed, thus avoiding the most catastrophic failure mode.

2.2 Plastic hinge failure

Also very common during earthquakes, the flexural plastic hinge failure mode occurs at the column ends. Spalling of concrete cover, failure of transverse steel reinforcement and buckling of the longitudinal reinforcement are typical for this failure mode. (Figure 1, b); c))

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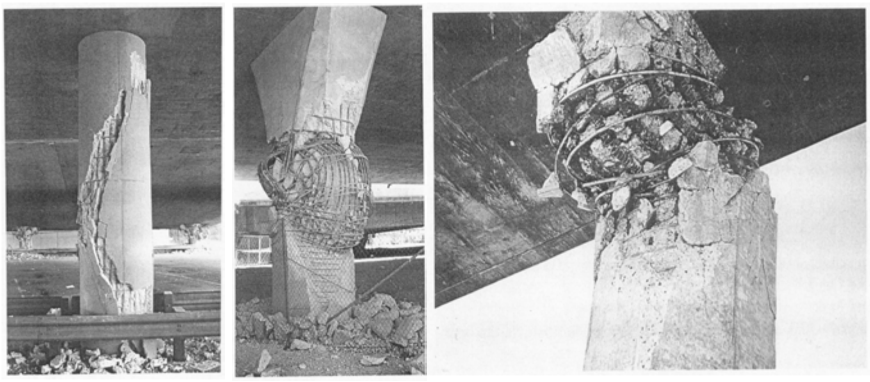
Since generally large flexural deformations occur, this failure mode is less brittle than the previous one and thus considered as much desirable.

2.3 Lap splice failure

This problem mostly happen in cases where the longitudinal reinforcement has been lap spliced in potential plastic hinge regions, with maximum moment values are likely to occur. Under the lateral forces induced by earthquakes, the splices may fail resulting in loss of capacity for undertaking large deformations.

The retrofitting procedure should end in a clamping device for the longitudinal steel reinforcement in order to prevent the loss of structural integrity of the column. This way, it will be able to sustain larger deformations, the failure being a more ductile one.



a) b) c)

Figure 1. Failure modes due to lateral (seismic forces) in case of columns: a) progressive shear failure; b) buckling of longitudinal steel reinforcement; c) flexural plastic hinge failure [2]

3. USE OF FRP COMPOSITE MATERIALS FOR COLUMN RETROFITTING

The traditional methods for column seismic retrofitting consisted in RC or steel jacketing. Apart from the disadvantages related to the increase of the column own weight and the economical inconvenient these methods introduced a new problem. Together with the relative enhancement of mechanical properties, these jacketing procedures significantly increased the stiffness of the column. The increase in stiffness induced supplementary seismic forces in the column.

Katsumata (in 1987, 1988) was the first to suggest the use of FRP composites for the retrofit of columns with problems related to seismic resistance.

Later on, two approaches were defined for the column retrofitting using FRP composite materials: (1) retrofit methods focused on the increase of ductility, and (2) retrofit methods focused on the strength enhancement. [1]

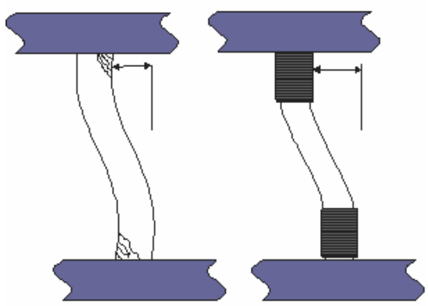


Figure 2. Ductility increase of RC column using FRP composite materials

The first method relies on bonding FRP plates in order to increase the flexural strength of the member; the second method consists in wrapping FRP materials having the fibres oriented in the hoop direction of the column. The result is desired to be a column that has an improved capacity for energy absorption.

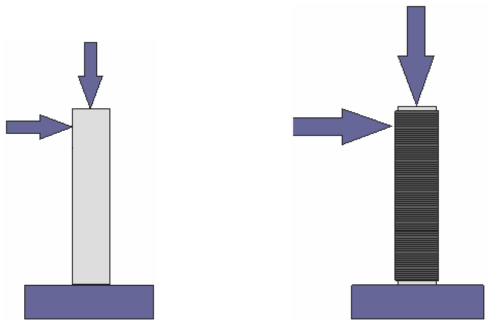


Figure 3. Strength enhancement of RC column using FRP composite materials

3.1 FRP jackets with fibres oriented in the hoop direction

The well known procedures of wet laying-up of fibre sheets or winding of fibre strands may be used using resins are also suitable when the shear capacity and ductility are to be enhanced.

The fibres will generally oriented in the hoop direction of the column, either the wrapping is performed on site or there are applied the previously prefabricated jackets. (Figure 4) Under lateral forces, the tensile stresses developed in the FRP fibres directly contribute to the shear resistance of the retrofitted column.

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A much greater ductility is obtained by the confinement resulted from flexure, increasing the strength and the concrete ultimate strain.

Figure 4. Shear strength enhancement of RC column using FRP composite materials: a) discrete rings with hoop oriented fibres; b) wet-laid up continuous jacket; c) prefabricated jacket

In case of shear strengthening, it is recommended that the entire column height should be covered by the FRP jacket. If other results are desired, the wrapping should be performed only in the region with the plastic hinge occurrence hazard or the lap splice clamping lengths. The jacket should be prevented from any direct axial loading.

When the shape modification of the column section is considered, the wrapping must be realized only in the region of the plastic hinges; any direct loading of the supplementary concrete or FRP jacket must be also avoided. (Figure 5)

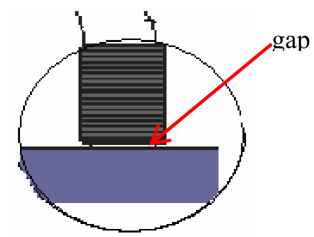

Figure 5. Imposed gap for preventing direct loading of the FRP jacket

3.2 FRP plates longitudinally bonded on the column

When the column is subjected to important axial loads, the lateral confining FRP jacket induces also an important flexural strength enhancement. Yet if not enough, this flexural capacity may be increased by additional longitudinally disposed FRP fibres (sheets or plates bonded on the longitudinal direction of the column).

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The combined effect of both longitudinal and lateral oriented fibres may be specifically positive in case of slender columns presenting low flexural capacities (Figure 6). When applied, this system directs the flexural failure of the column towards the plastic hinge regions.

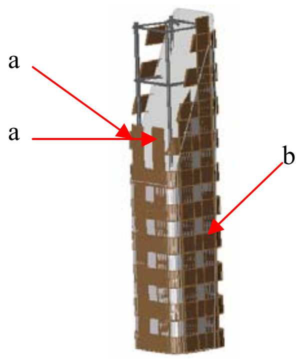

Figure 6. Combined shear and flexural strength enhancement of RC column using FRP composite materials: a longitudinally bonded FRP plates; b) discrete rings in hoop direction

4. COMMON TESTING METHODS FOR EVALUATING THE FRP COMPOSITES EFFECTS ON LATERALLY LOADED COLUMNS

The basic testing procedure used in order to evaluate the effect of FRP composites retrofitting of columns is laterally loading the columns in cycles while they are subjected or not to simultaneous axial loads. (Figure 7)

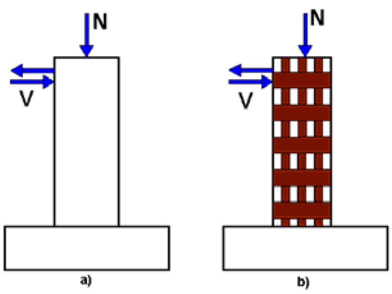

Figure 7. Typical test procedure for seismic retrofitted columns: a) control test specimen; b) retrofitted element

The first such a test was performed as mentioned by Katsumata *et al.* (1987, 1988) when introducing the idea of FRP composites retrofitting of columns. Both circular and rectangular columns retrofitted or not, were subjected to combined axial and cyclic lateral loads. [1]

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Among the parameters that are considered in tests there are:

- the shear span (level of lateral cycling load V related to the bottom end of the column);
- the cross-sectional dimensions of the section;
- the axial force ratio;
- the characteristic strength of the concrete;
- the CFRP reinforcement ratio (and the related strength ratio).

Strain gauges applied both on the concrete surface and the FRP composite material should provide data concerning the variation of stress and strain state in the two materials as the element is loaded. The loading start with the axial loading of the column (up to a level that will remain constant afterwards) then, lateral force is induced (most commonly as a lateral controlled displacement). Cycles of positive and negative lateral forces (change in direction of loading) and loading/unloading cycles are used. [3]

The targeted result data include the increase in shear and/or flexural strength, the increase of ductility, the failure mode, and load displacement relationships.

5. DESIGN ASPECTS IN CASE OF SEISMIC RETROFITTING OF RC COLUMNS

A rather common analysis that is used in case of shear capacity of RC columns retrofitted with FRP composites implies three factors (equation (1)) [4]:

$$V_r = V_c + V_s + V_{frp} \tag{1}$$

where,

V_r -total factored shear resistance;

V_c - factored shear resistance attributed to concrete;

V_s - factored shear resistance attributed to the transverse steel;

V_{frp} - factored shear resistance attributed to the FRP.

The required thickness of the FRP wrap may be computed considering the last term in equation (1) as a function of FRP wrapping parameters (equation (2)).

$$N_b \cdot t_{frp} = f(\Phi_{frp}; E_{frp}; d(D); \theta) \tag{2}$$

where:

$N_b \cdot t_{frp}$ -total thickness of FRP wrap;

Φ_{frp} - resistance factor for FRP;

E_{frp} - FRP modulus of elasticity;

$d(D)$ - side length (diameter) of the cross-section;

θ - angle of principal compression strut to the column axis or the shear crack inclination.

6. CONCLUSIONS

Columns are very fragile members when laterally loaded. As main parts of frames, retrofitting procedures for frames should focus on them.

FRP composite materials are very suitable for increasing shear/flexural strength capacity and ductility (energy absorption capacity). Shear failure mode is the most dangerous one for columns as it is brittle, explosive. Should an earthquake occur, shear failure gives virtually no time for eventual escaping actions for people.

Modern retrofitting methods imply the use of CFRP sheets disposed in the transversal (hoop) direction and longitudinally bonded FRP sheets/ plates.

Tests methods try to simulate the combined action of cycling lateral load with the (permanent) axial load.

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