DURABILITY OF THE REPAIR MATERIALS AND REPAIRED STRUCTURES

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ABSTRACT

The concern about durability of concrete repair has become the most challenging problem in the concrete industry today. Numerous repairs have been completed but little attention is given to long-term performance. The repair cost is high and it is continuously increasing. The cost of repairing the repaired concrete is even much higher. This necessitates the need for a durable and economical repair system.

Unfortunately, the durability of repair for structural and non-structural element is a broad subject but the right selection of repair materials, surface preparation, application of the materials, construction practice and inspection are very important factors for producing durable repair. In addition, influence of environment, design details, specification for repair materials are equally important. These factors are interrelated and must be considered when designing for a durable repair.

Availability of such data is essential for the road toward establishing a methodology of designing for durability and performance criteria for a durable repair materials and system. Some details about the effects of the main factors that may influence the durability of repair materials and design guidelines are outlined in this paper.

Keywords: *concrete repair, compatibility of repair material*

الملخص

لقد اصبح الإهتمام بمتانة إصلاح الخرسانة حالياً يمثل عنصر ضغط اساسي في عالم صناعة الخرسانة. فرغم انه قد تم تنفيذ عدداً كبيراً من الإصلاحات الخرسانية إلا أن الأداء لتلك الإصلاحات على المدى الطويل لم يلقى الاهتمام الكافي. إن عملية الصيانة مكلفة جداً ويزداد سعرها باستمرار، ولكن صيانة مآتم صيانته مسبقاً اكثر كلفة من الصيانة نفسها. وهذا يحتم الحاجة لنظام صيانة عالي المتانة.

إن موضوع متانة الإصلاح للعناصر الإنشائية وغير الإنشائية يعتبر واسع جداً ولكن اختيار مواد الترميم الصحيحة وتجهيز السطح واستخدامها بصورة سليمة والعوامل الميدانية تعتبر من العناصر الهامة التي تؤثر على متانة الإصلاح.

أيضاً فان تأثير الظروف البيئية والتصميم الواضح والمواصفات لمواد الترميم لها نفس الأهمية. والجدير بالذكر فان تلك العناصر مترابطة مع بعضها ويجب اعتبارها عند تصميم الإصلاح.

توفر تلك المعلومات ضروري جداً في الطريق نحو ايجاد طريقة صحيحة لاختيار مواد الترميم لإصلاح الخرسانة وطريقة استخدام وتصميم تلك المواد للحصول على نظام ترميم ذو متانة عالية. وتتعرض هذه الورقة بشئ من التفصيل للعناصر الأساسية التي تؤثر على متانة الإصلاح وشئ عن إرشادات التصميم للترميم.

1. INTRODUCTION

Deterioration of the infrastructure has become the most significant challenge facing the engineer and the construction industry. Therefore, the concrete repair has become one of the most industry's emerging sectors. Numerous repairs have been completed in the Gulf Region but, unfortunately, not well documented as regards to the long-term performance. Not only that but very little has been done to establish a methodology of design for durability and performance criteria for durable repair materials and repair system. Furthermore, manufacturers' data sheets, the only resource available in the market about the properties of the repair materials, do not contain all the essential data required about the properties of the repair materials. They tend to use different tests and standards to evaluate the performance of their products. Also, many standard tests used to prepare the sheets are modified arbitrary; some modifications are deficient or provide unrealistic results [Emmons et al., 1994]. This situation resulted in controversy and confusion about the information provided in the manufacturer's data sheets. In addition, test methods, specimen size, restrain conditions, curing procedure; time of initial readings, temperature and humidity limits, and test duration further complicated the comparison between the information provided in the data sheets from different manufacturers.

On the other hand, a wide variety of repair materials are now available for the design engineer, however, it seems very difficult to select the right repair material. The difficulty, in addition to the aforesaid points, also arises from the lack of generally accepted performance criteria guidelines to the repair technology and the advanced engineering concepts. The main factors that should be considered to select durable repair materials and system include but not limited to: properties of the repair materials, type of application (structural or non structural repair), the degree of adhesion, shrinkage, thermal movement, cracking characteristics, chemical passivation of embedded steel, ease of application, chemical resistance, overall performance, material cost and labor. Some of these are discussed in brief details in the next sections.

It should, however, be stated here that this paper is aimed at to provide the factual information about the repair materials to the practicing engineers and other users. At present, the information pertaining to this subject is scarce and at times misleading. In order to facilitate

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the better understanding of the behavior of the repair materials and system, greater efforts are needed to transfer such information and facts into a form which the practicing engineers can implement.

2. REPAIR MATERIALS

Numerous types of repair materials are now available in the local market and can be mainly categorized into three groups: Cementitious mortars, polymer modified cementitious mortars, and resinous mortars.

Cementitious materials are cheaper than the resin mortars and have compatible thermal expansions and movement characteristics with the concrete substrate. Grout and mortar are highly shrinkable materials therefore when applied thickly they tend to increase the relative drying shrinkage between the substrate and the overlay materials. This may lead to debond the repair materials. In addition, if the grout or the mortar dries out before applying the overlay it will cause great reduction of the bond between the two materials. Cementitious materials are easier to mix, can be used in large volumes and have lower exotherms during curing than the resin materials. However, their low tensile strength, low extensibility, and stress induced by drying shrinkage are combined to produce cracks in concrete repair.

Polymer modified concrete has an excellent durability, high bond characteristics to substrate, good workability, high resistance to abrasion and is easy to apply. However, it is expensive, has high tendency toward plastic shrinkage and, slightly, sensitive to high and low temperature at the time of application.

Epoxy materials are well known and accepted materials for the repair. However, there are many problems associated with the use of epoxy materials. Firstly, they do not allow moist to evaporate. This may cause some internal pressure which may cause debonding between the substrate and the epoxy. This is particularly the case in humid areas where the moist can reach the bond line from within the old concrete. Secondly, the pot life for epoxy materials is critical and in hot climate, as is the case in Gulf Region, this may not be more than few minutes. Therefore, there will always be great chance that they harden before the overlay could be placed. In such cases the epoxy materials will act as barrier between substrate and repair materials and significantly reduces the bond. The seriousness of such problem may be more pronounced when repairing upright surfaces. In general, resin based materials are preferred where thin sections have to be applied to benefit from the low permeability of resin materials together with good adhesion and lack of special curing requirements. For large repairs, however, it is preferable to use cement-based materials.

Typical values of the important mechanical properties for the three groups are presented in Table 1 (Cusson And Mailvagan, 1996).

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Table 1: Classification of the repair materials and typical values of their mechanical properties

Mechanical properties	Cementitious mortars	Polymer modified mortars	Resinous mortars
Compressive strength (MPa)	20-50	30-60	50-100
Tensile strength (MPa)	2-5	5-10	10-15
Elastic modulus in compression (GPa)	20-30	15-25	10-20
Coefficient of thermal expansion (°C × 10^{-6})	10	10-20	25-30
Water absorption (% by weight)	5-15	0.1-0.5	1-2
Maximum service temperature (°C)	> 300	10-33	40-80

3. STRUCTURAL AND NON STRUCTURAL REPAIR

Structural repairs are used to restore the design load bearing capacity of under-designed member. However, for non-structural repair it is used to improve the surface appearance, reduces the permeability, protects reinforcement or improves the abrasion resistance. In practice, there is a little differentiation shown between structural and non-structural repairs. Billions of Saudi Riyals are spent every year for removing and replacing deteriorated concrete structures. Patching repair may not directly address the root cause of the concrete or the structural deterioration. Repaired structures often continue to deteriorate and eventually demand significantly more expenditure when repairing the repair.

Infrastructures are usually built to stay in service for the intended design service life. However, in addition to selecting durable repair materials, there are some instances when the whole structure or part of it is in need for some engineering interference for rehabilitation or renovation. Some of these instances are when:

1. The integrity of the structure is impairing due to the effect of the hostile environment such as salt attack.
2. There is a need to increase the capacity of the existed structure to meet the new standard or to carry more loads than what was originally designed for.
3. There is a need for some innovation that requires essential changes in the structural layout such as moving some of the supporting system which may result in some stress redistribution that may cause some parts of the structure to be overloaded.
4. The structure suffers from time deterioration and there is a need for rehabilitation.
5. There are some design or construction errors.

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4. COMPATIBILITY

Concrete repair must successfully integrate new materials with old materials, forming a composite capable of enduring the exposures of use, the environment and time. The compatibility and interaction of a repair to an existing concrete structure can affect the durability of the repair and even the durability of the structure. It must therefore have physical and chemical properties, which are consistent with the substrate concrete, and with the design and use of the structure to which it is applied.

The factors affecting the compatibility of the repair systems are summarized in Figure 2 [Emmons and Vaysburd, 1996, and Khan et al., 1999]. In particular, dimensional compatibility controls volume changes which aid to prevent or minimize cracking. Repairs are of substantially higher risk of cracking than other forms of construction. In addition to volume changes, a concrete repair can be classified as either stress carrying (structural repair) or protective [Morgan, 1996 and Emmons 1995]. Structural repairs, however, must also be protective and the electrochemical, chemical and permeability compatibility of the repair system must be considered to ensure this. The concept that a low permeability repair material will ensure long-term durability as in new construction is a fallacy. The diverse range of environments created by the interaction of repair with the substrate and the environment to which the structure is exposed can dramatically affect the durability of the entire repair system.

4.1. Dimensional compatibility

Drying shrinkage and thermal expansion are the two most significant characteristics that play the major role in the dimensional compatibility of the repair materials. When the drying shrinkage of the repair material is high this means that the relative movement between the substrate and the repair material (that is at the boarder line between the two materials where a zero relative shrinkage is required) is high. This, of course, will jeopardize the durability of the repair. The values reported by the material suppliers are always questionable with regard to the drying shrinkage of the repair materials. Emmons, et al. [1994] classified the repair materials based on their shrinkage properties and found that only 15% out of 46 surface repair materials tested can be labeled as low shrinkage, despite the manufacturer's claims that the materials are expansive, non-shrinkage, or shrinkage compensating. Similar conclusions were reported by Al-Ozaib [2000] and Maddallah, [2001]. Most good quality concrete will have shrinkage in the range of 350 to 650 microstrains. Suppliers of repair materials often report shrinkage values as a percentage instead of as microstrain because the number looks smaller even though it is not. For instance, when they say very low shrinkage material and show is as a percentage, for example by writing the shrinkage is less than 2%. This implies that the value 0.19% is possible. This gives a possible strain of 1900 microstrain which means 6 to 3 times that of the normal concrete.

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On the other hand, the difference in thermal expansion between the repair material and the substrate may highly affect the durability of the repair. For instance the coefficient of the thermal expansion for the epoxy resin is about 8 times greater than that of the concrete. For horizontal surfaces the effect can be highly reduced by adding more aggregates to the epoxy mortar, the mix will be of low viscosity but it can be easily used for horizontal surfaces. However, for vertical or overhead surfaces the low viscosity non-thixotropic (sag) epoxy resin can not be used. Thus, a mix with high viscosity and high coefficient of thermal expansion can be used.

Furthermore, the difference in the modulus of elasticity between the repaired and substrate materials may also become a source of repair incompatibility problems. For instance, when using repair of high modulus of elasticity (higher than that of the substrate) then the weaker point in the repaired section may be the bond line itself. Also, with vertical repair, the material with higher modulus will carry most of the load. That may result in stress concentration and as a consequence to that a total failure to the repair system and probably to the whole structure.

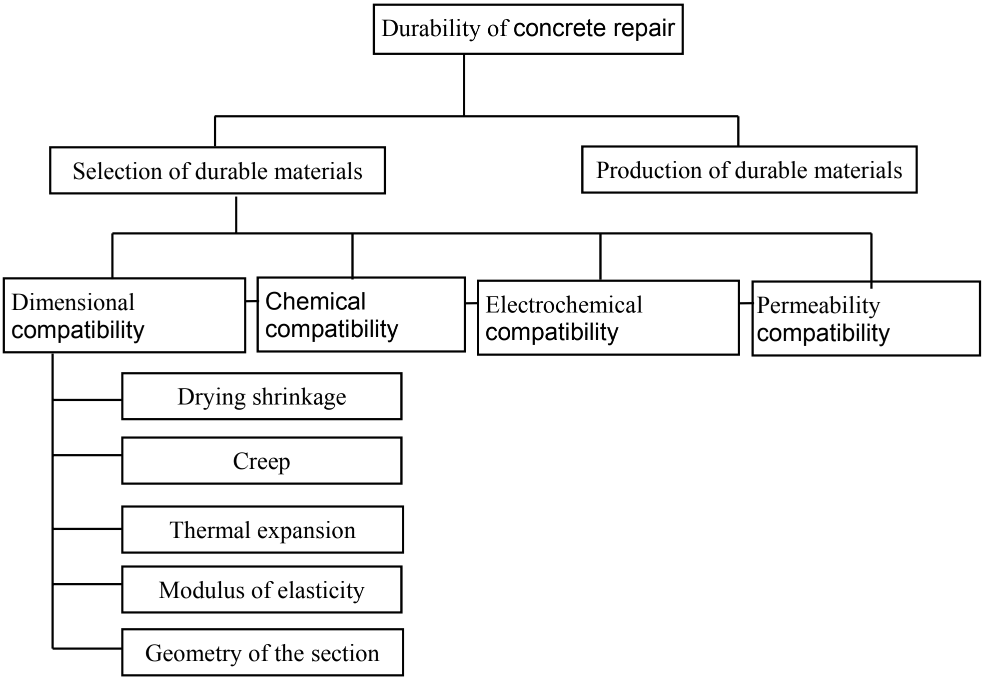

Figure 1. Main factors that affect compatibility between repair material and substrate.

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4.2. Chemical compatibility

When selecting a repair material the chemical compatibility must be considered and evaluated. Under normal condition, reinforcing steel embedded in Portland cement concrete exhibited a high degree of resistance to corrosion. This is attributed to the presence of a protective ferric oxide film that forms on steel when it is embedded in fresh concrete. This film is highly alkaline environment present in concrete with a pH of 12.5 to 13.5, providing continued protection for the steel. However, some of the repair materials have low pH value. If such materials are used then there will be no protection for the reinforcement against corrosion. In such cases special care must be considered to assure enough protection for reinforcement against the ingress of materials that may promote corrosion process.

4.3. Electrochemical compatibility

It is well known that a high resistance concrete has a high resistance to current flow and therefore the corrosion tendency is weak. It is assumed that a limiting resistance of the order of 300-600 Ω is sufficient to prevent corrosion progressing. However, when repair materials have different electrical resistivity, even if it is higher than that of the concrete, the reinforcing steel will be more susceptible to corrosion. It has been reported (ACI Committee 546, 1996) that differentials in electrical potentials between the repair material and the substrate concrete could increase corrosion activity, resulting in premature failure. However, such a condition can not be generalized and should be evaluated on the case-to-case bases for every repair conditions.

4.4. Permeability compatibility

There is an inverse relationship between the permeability of concrete and the rate of its deterioration. Therefore, there is always a tendency to produce concrete with least permeability. This is also true when selecting the repair materials. However, if impermeable repair materials are used, moisture that may rise up from the substrate can be trapped between concrete and the repair materials. In areas subjected to freeze and thaw cycles this may cause failure to repairs, concrete or both. In the Gulf Region such a condition may not prevail.

5. BOND STRENGTH

A major factor that influences the durability of the repair is the bond strength between the new material and the substrate. Several factors address the adherence between the two materials. These include: the properties of the substrate, the roughness, microfractures and porosity of the substrate, the properties of the repair materials, curing procedure of the repair materials, the loading conditions (intensity, type, and direction), environmental (sun, cold or hot weather, dry or humid and daily cycles) and serviceability conditions. A durable repair may not be produced unless the effect of all such factors is considered during the design stage and when selecting the repair materials.

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6. MECHANICAL PREPARATION OF THE SURFACE

Mechanical preparation of the surface will cause some microfractures to the surface which will decrease the maximum possible bond strength between the repair material and the substrate. However, sand blasting and water jet may not cause microfractures and produce better surface for bonding [Silfwerbrand, 1990]

It is common practice to use mechanical methods to roughen the surface but, as indicated earlier¸ this may result in concrete microfractures. However, utilization of the mechanical roughening in practice with the apparent success does not necessarily mean that the full capacity of the bond is being utilized. When using 20 to 30% of the capacity, production of 50% of the capacity will be sufficient. This, however, is not an indicator that the maximum capacity of the bond has been produced. The consequences of neglecting over 50% of the bond capacity are obvious.

7. WETTING THE SURFACE OF THE SUBSTRATE

Many repair materials require the substrate surface to be at saturated surface dry (SSD) condition. However, it is not unusual to see excess water on the surface rather than just SSD. The presence of water at the bond line at a quantity more than required may cause the cement paste to be diluted which may lead to increase w/c ratio at that area, resulting in lower strength and more shrinkage at the bond line where the opposite of the two characteristics are highly needed.

8. CONSTRUCTION PRACTICE

Construction practice in repair is the paramount factor in producing quality of the repair at all stages from preparing and delivering the material to its final position. For example, at the mixing stage the product must be workable enough to be delivered to the substrate with the specified workability. Even the manufacturer recommendations for using the materials may not be valid under all environmental conditions. For instance, Li et al. [1997] reported that the manufacturer recommendation for producing patching repair resulted in a too dry mix such that additional water was needed to attain adequate workability. Changing the quantity in the mixing water from batch to batch may increase the relative drying shrinkage within the repair materials which may also result in delamination of the repair materials.

The main factors that usually influence the durability of the repair are presented in Fig. 2. However, in practice, some other factors may dominate other factors in selecting the repair materials although other materials may provide better compatibility with the substrate materials. For example, accessibility, life cycle costing, size and geometry of the repaired part, presence of reinforcement in the repair, effect of section stiffness. However, a summary of the important properties to be considered when selecting repair materials are listed in Table 2 [Cusson et al., 1996].

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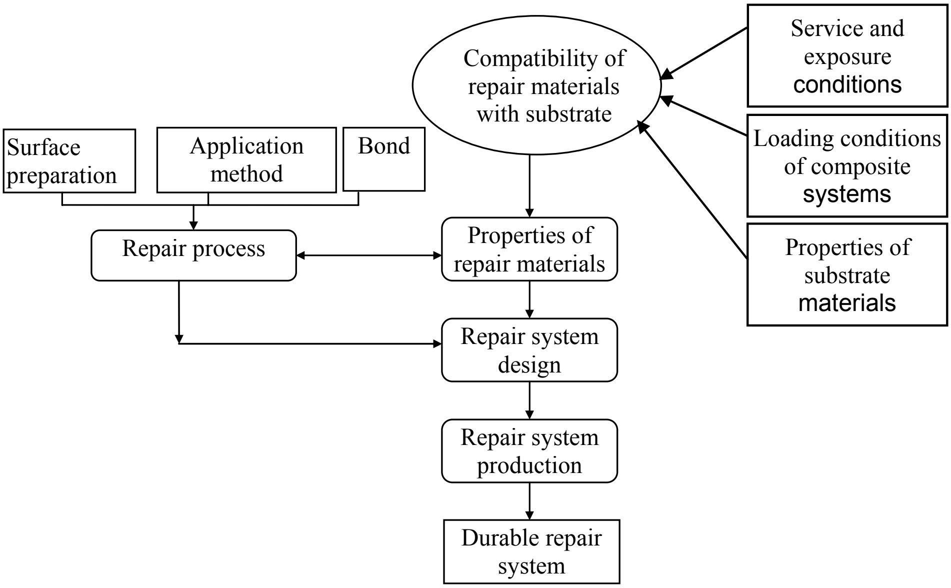

Figure 2. The main factors that affect the durability of concrete repair

Table 2. General requirements of patch repair materials for compatibility

Property	Relationship of repair material (R) to concrete substrate (C)
Shrinkage strain	R<C
Creep coeff. (in compression)	R<C
Creep coeff. (in tension)	R>C
Thermal expansion coeff.	R=C
Modulus of elasticity	R=C
Poisson’s ratio	R=C
Tensile strength	R>C
Fatigue performance	R>C
Adhesion	R>C
Porosity and resistivity	R=C
Chemical reactivity	R<C

9. GUIDELINES FOR SELECTING DURABLE REPAIR MATERIALS

The selection of repair materials and repair execution must be evaluated in light of in-service conditions and the factors discussed above. Some systematic rules and guidelines should be set for using the repair materials such that the properties of the repair materials and method of selection are clearly identified. On the other hand, a schematic representation for the method that can be used to carry out a reliability structural repair is shown in Fig. 3 [Yao et al., 1999]. Rules and guidelines can only be prepared after conducting some extensive laboratory and field tests. Correlations between the laboratory test results and the field performance could also be established. This, however, can be executed in a step-by-step manner. In order to be effective, the guidelines should be honored and protected by some engineering committee and supported by some kind of reasonable enforcement. Any changes in the material properties by the manufacturers have to be reported to the committee. The design guidelines should also leave some rooms for the environmental and site conditions.

Several countries have already specified some performance criteria and guidelines for selecting the repair materials [Emmons et al. 2000]. The guidelines put some limits on some engineering characteristics such as compressive strength, tensile strength, modulus of elasticity, bond strength, permeability and drying shrinkage.

10. CONCLUSIONS

The paper outlined the problem of repair deterioration and the need for selecting and producing a repair system that can with stand the environmental and loading conditions. This however, is a general statement and attaining such a huge task is not easy. It requires lots of laboratory tests, field work, and continuous cooperation between the industries, the practitioners and the Universities. Thus, the concern about the durability of concrete has become the most challenging problem in the concrete industry today. Very little attention is given to long-term performance, influence of environment, design details, specification for materials and to the method of repair. Therefore, there is an urgency for an effective repair techniques and more reliable assessment methodologies and a rational strategy and innovative remedial methods. Also, the design engineers should deal with infrastructure repair as a profession as they deal with designing the new structure.

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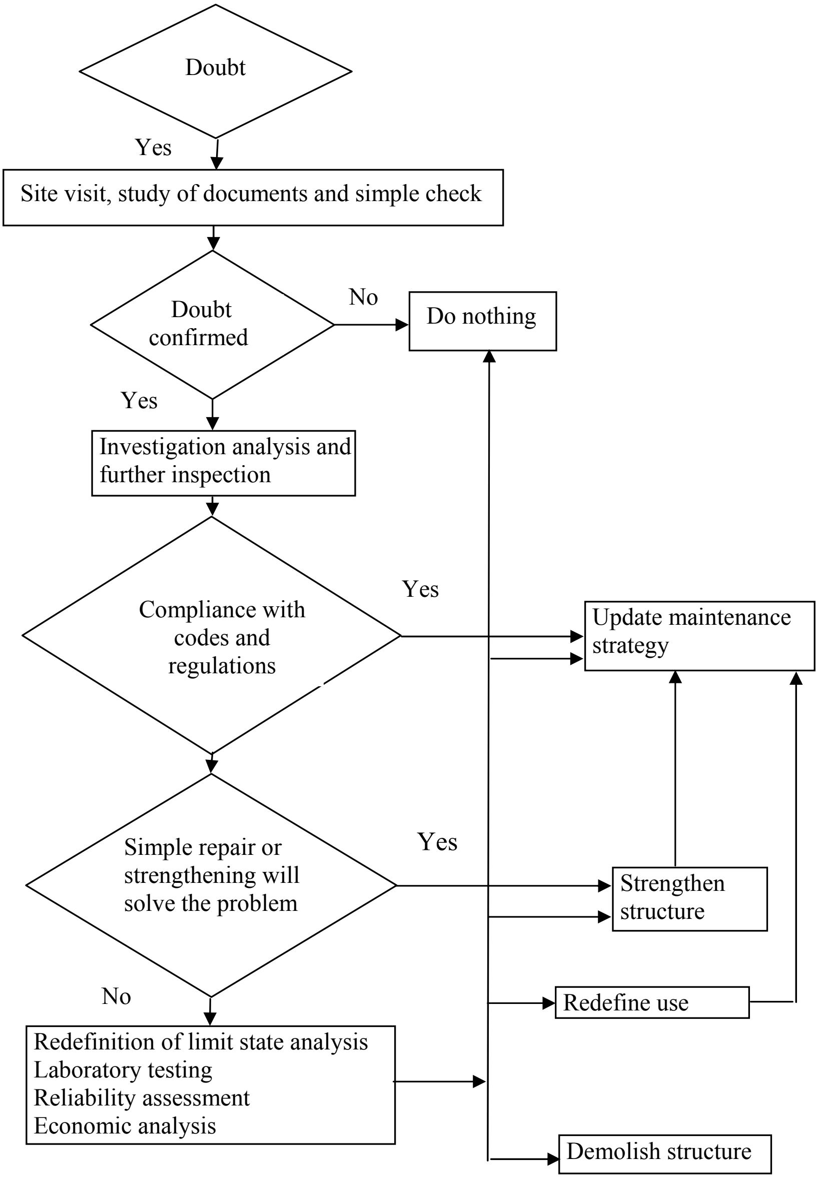

Figure 3. Reliability procedure in deciding the method of repair.

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