A comparison study on Australia, Eurocode, and US reinforced concrete structure repair codes

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Abstract. Currently, there is no local standard on reinforced concrete structures repairing in Malaysia. The aim of this study is to discuss the similarities and differences of the reinforced concrete structure repair codes of Australia, Eurocode, and United States.In the methodology and work plan stage, preliminary decision for concrete repair is made after the structural assessment. Next, repair work is conducted in relation to the general planning. Lastly, repair products applied in the system are ensured to be mutually compatible in order to accept the repair work. According to the 11 principles listed in EN 1504-9, concrete damages are classified as concrete defects and corrosion on reinforced concrete structure. SA HB 84:2018 is using the fundamental principles of EN 1504 as the main reference. Similarly, all three codes highlight the reinforcement corrosion as the primary reason of concrete damage. The main difference between ACI 546R-14 and EN 1504 is ACI 546R-14 provides no principle for all intended uses in repair works. Two case studies of reinforced concrete structure repairing for irrigation control structures and low-cost flat building are discussed. The case studies reveal a possibility of combining the strengths of a selected standards in reinforced concrete structures repair works.

1 Introduction

There are numerous construction projects carried out annually in Malaysia. If the reinforced concrete structures are constructed with quality workmanship, application of suitable materials and procedures, it may not need to be repaired soon, otherwise, repair works on aged and new concrete reinforced structures are required. According to Sahafnia [1], some of the primary causes of reinforced concrete structure deterioration are accidental loading, construction errors, chemical attacks, freezing and thawing, changes of temperature, and corrosion. In addition, corrosion of reinforcement system further triggered by external factors and internal factors. Carbonation, chloride attack and moisture content are classified as external factors. Internal factors are concrete cover, water-cement ratio and aggregate gradings [1]. These factors stimulate the production of rusts that might expand the original concrete volume and generates a significant expansive forces towards the surrounding [2].

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Currently, there is no local standard on reinforced concrete structures repairing in Malaysia. As an alternative, the engineers in Malaysia are conducting the repairing projects according to the Eurocode, American standard and other relevant concrete repair codes. Thus, it is important to understand the fundamental principles applied in the reinforced concrete structure repairing works. Also, it involves different requirements and considerations for each standard. The engineer could provide the reinforced concrete structure repairing work solutions based on the different methods and assessments stated in the codes. The aim of this study is to discuss the similarities and differences of the reinforced concrete structure repair codes of Australia, Eurocode, and United States. The findings are further supported by 2 case studies.

2 Methodology and work plan

The outline of methodology and work plan is summarised in the Fig. 1.

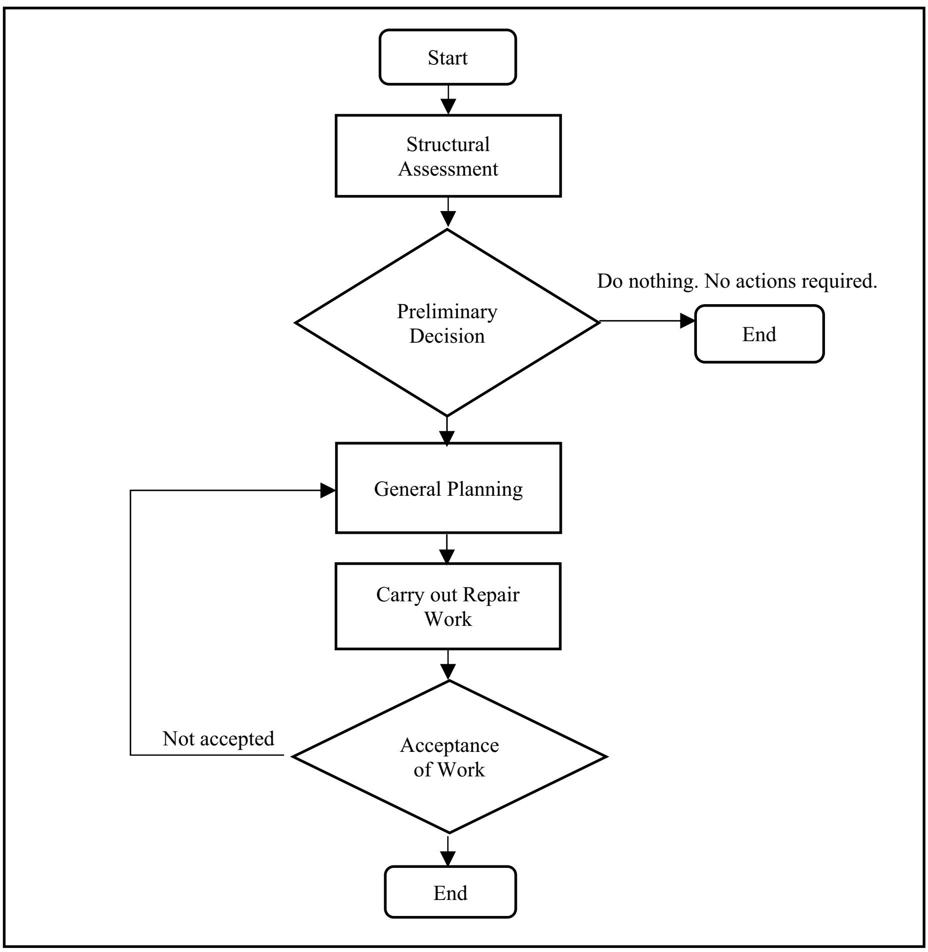

Fig. 1. Outline of methodology and work plan.

Initially, structural assessment was performed to narrow down the broad scope if it exhibits damage evidence, cracks, deficiency of structure or inappropriate behaviour. The surface structure and contiguous members were also taken into consideration throughout the investigation involving connections in the system. It is followed by common distress signals which were found to be an easier starting point for investigation. Some of the signals were surface spalling, deposit of rusts, movement of members or cracks.

It is important to determine whether the situation needs to be repaired immediately or postponed if there is any other work that must be completed first. To fully understand the problems, evaluation was reinforced by referring to the data from several laboratory tests. Upon the completion of structural assessment, deterioration mechanism was determined to find the causes and impact of deficiency. Further preliminary decisions were:

(i) Do nothing; no necessary actions to be taken.
(ii) Recalculate the capacity of the structure when it is exposed to aggressive sources and inhibit the deterioration process.
(iii) Minimize the effect of deterioration by restoring the structural capacity in most common situation.
(iv) Demolition of the structure, completely or partially (worst scenario).

In general planning stage, strategy in selecting the recommended repair materials and methods were considered based on the 11 principles from EN 1504 and/or ACI 546R-14 and/or SA HB 84:2018. Normally, selections that may further contribute or fasten the damage are avoided [3]. The goals of general planning were involved in judgement of budget, benefits, and future restriction. As a common rule, the choices of product or system is projected with different possibilities of future deterioration [4].

After conducting the general planning, repair works were carried out with intended requirements of products, substrates, specifications, and properties. Requirements between a structural repair and non-structural repair may vary, depending on the choices of repair personnel and selection of remedial system. In structural repair, the primary focus is intended to maintain the strength and stiffness for service loading. For non-structural repair, the purpose of repair only focuses on aesthetic value and not intended to rectify the durability and strength.

The primary objective of executing repair works is to prolong, refurbish or strengthen the conditions of a reinforced concrete structure. Consequently, repair products applied in the system are expected to be in achieving the acceptance of work.

3 Result and discussion

3.1 Similarities of EN 1504, SA HB 84:2018 and ACI 546R-14

SA HB 84:2018 is using the fundamental principles of EN 1504 as the main reference. According to Clause 4.3 in EN 1504-9, assessment process is conducted to check the causes of the defect and existing structural conditions [5]. Similar to ACI 546R-14, evaluation of concrete damages is related to present structural conditions, corrosion process, environmental conditions and construction documents.

Next, all three codes highlighted the main reason of concrete damage which was due to corrosion of reinforcement system. Similar to the concrete preparation, reinforcement system also required proper preparation such as removal of surrounding concrete and cleaning from contaminants. For that, formation of rust, oil, deleterious materials or dust should be removed from the reinforcement systems. EN 1504 and SA HB 84:2018 agreed to clean and retain the embedded reinforcement system to surface purity of Sa 2.5 or Sa 2.0. Common methods involved for maintaining the purity are barrier coating and mixture of coatings and pigments. A minimum distance of 20 mm between chloride contaminated concrete and reinforcement are advisable during concrete removal. The distance between concrete surface and reinforcing system is to control the spread out of carbonation and chloride ingress. For the cleaning of reinforcement system, hydro demolition is the most suitable as suggested in all three codes. Annex A.7.3.2 in Part 10 of Eurocodes further suggested to operate with water pressure in range of 18 MPa to 60 MPa. Apart from high pressure water blasting method, SA HB 84:2018 and ACI 546R-14 also outlined sandblasting techniques in the final stage of cleaning the steel. Protective coating is also highlighted in all three codes to overcome the aggressive environment after cleaning of reinforcement.

Furthermore, EN 1504 and ACI 546R-14 proposed to apply cementitious or polymer materials in bonding process. Relevant test methods for performance of products are provided with specific references in both codes.

Lastly, EN 1504 and ACI 546R-14 recommended to conduct a maintenance program upon the completion of repair works. Since there are failure possibilities in repaired work, both codes suggested to include periodic engineering inspections with specific dates and areas to be checked. Preparation of documents for future maintenance are advised in ACI 546R-14 through the coverage of warranty. Similarly, EN 1504 suggested to prepare a document of detailed invoice when dealing with maintenance program. Table 1 shows the summaries of the similarities among the three codes.

Table 1. Similarities of EN 1504, SA HB 84:2018 and ACI 546R-14.

Similarities	EN 1504	SA HB 84:2018	ACI 546R-14
Scope of concrete defects assessment	Clause 4.3 (ENV 1504-9)	Chapter 4.2	Chapter 1.2.1
Concrete removal method	Clause 7.3.2, Annex A.7.2.4 (EN 1504-10), Only Applicable for Hydrodemolition	Chapter 6.4	Chapter 3.2, Table 3.2.4
Handheld breaker as most common concrete removal method (small area)	Not Applicable	Chapter 6.4.1	Chapter 3.4.2.4.1
Hydrodemolition for larger removal of concrete defect area	Clause 7.3.2, Annex A.7.2.4 (EN 1504-10)	Chapter 6.4.1	Chapter 3.2.4
Concrete surface preparation	Clause 7.2, Annex A.7 (EN 1504-10)	Chapter 6.4.2	Chapter 3.3, Table 3.3.2
Reinforcement surface preparation	Clause 7.3, Annex A.7 (EN 1504-10)	Chapter 6.4.3	Chapter 3.3, Table 3.3.2
Surface purity of Sa 2.0 to Sa 2.5	Annex A.7.3.2 (EN 1504-10)	Chapter 6.4.3	Not Applicable
Application of cementitious or polymer material in bonding process	Clause 8.2, Annex A.8.2.1 (EN 1504)	Not Applicable	Chapter 4.4
Maintenance program	Clause B.8	Not Applicable	Chapter 1.2.8
Quality assurance and quality control	Clause 9, Clause A.9	Not Applicable	Chapter 1.2.7.3.2, Chapter 3.4

3.2 Differences of EN 1504, SA HB 84:2018 and ACI 546R-14

ACI 546R-14 provides methodologies for contract documents, bid and negotiation process, and work execution. These repair methodologies are not covered in any part of the EN 1504 series. A detailed explanation of the types of repair contracts from scopes of lump sum, unit price and quantities of work are stated in ACI 546R-14. Besides that, preparation in bidding process to select the suitable candidate among several contractors are also considered in ACI 546R-14 [6].

Next, Clause 5.3 in Part 9 of Eurocodes outlined the factors in affecting the selection of appropriate repair works. The considerations are divided into general, health and safety, structural and lastly environmental factor [4]. However, design considerations in ACI 546R-14 are focused into current load distribution, compatibility of repair materials, creep and shrinkage, vibration, water and vapor migration, and lastly material behaviour characteristics.

According to Clause 6.2 in EN 1504-9, there are two tables (Table 1 and 2 in Part 9) of principles to be applied on specific repair methods, separately or in combination. Note that Principle 1 to 6 are in relation with deterioration caused by concrete itself. Principle 7 to 11 are related to deterioration from reinforcement corrosion. Clause 6.2.1 in EN 1504-9 further mentioned that the defects cause covered from Principle 1 to 7 are usually from mechanical, biological, chemical actions from surrounding, and lastly physical actions. For Principle 7 to 11, reinforcement corrosion is often triggered by losses (physical and chemical loss), contamination of concrete cover and conduction of stray electrical currents. The SA HB 84:2018 is using the fundamental principles of EN 1504 as main reference [7]. Among the 11 principles stated in EN 1504, SA HB 84:2018 are focusing on joint sealants, protective coatings, moisture control, patch repair system, corrosion inhibitors, cathodic protection, and corrosion control methods, and structural strengthening. ACI 546R-14 provides no principle to the user for all intended uses in repair works.

The concrete removal and surface preparation methods as mentioned in ACI 546R-14 are further supported with limitations and features. In addition, ACI 546R-14 also proposed diamond wire cutting hydro demolition, drilling, scrabblers, milling, gas blasting, presplitting and scalers in concrete removal methods. These concrete removal methods are unavailable in EN 1504 and SA HB 84:2018. In terms of surface preparation, chemical cleaning and acid etching are included in ACI 546R-14 but also not found in other two codes.

In ACI 546R-14, the discussion of reinforcement repair further classified several methods such as galvanized reinforcement, stainless steel reinforcement, stainless-steel-clad reinforcement, and composite non-metallic reinforcement. Grades 304 and 316 stainless steel materials are also highlighted for resisting aggressive environment [6]. Compared to EN 1504 and SA HB 84:2018, information of materials and steel grade are not available.

Furthermore, ACI 546R-14 categorised repair materials and protective techniques as the main contents, where these contents are further supported with advantages, disadvantages, application and referenced ACI Standard. Considering there is a need to examine the outcomes of the repair performances, relevant tests for quality control are not available in ACI 546R-14. In relation to EN 1504, Annex A.8.2.2 to 8.2.4 only recommended cementitious or polymer modified materials are used in conducting the bonding process. Information provided for the repair products are available in EN 1504, but the contents are quite limited especially for site application or installation conditions. Instead of focusing on repair products like ACI 546R-14, EN 1504 series give priorities to quality control of the performance after system and product applications. Annex A.9 in Part 10 provides a reference of the test method (observation) in different scenarios that allow the manufacturer to conduct test methods for conformity [5]. The differences of each code are simplified in the Table 2 below.

Table 2. Differences of EN 1504, SA HB 84:2018 and ACI 546R-14.

Differences	EN 1504	SA HB 84:2018	ACI 546R-14
Core of the contents	Repair Principles Related to Concrete Defects and Reinforcement Corrosion, Test Methods for Conformity, Quality Control	Application of Fundamental Principles of EN 1504	Repair Materials, Concrete and Reinforcement Repair Techniques, Protective Systems, Structural Repair and Strengthening
Repair methodologies	Not Applicable	Not Applicable	Contract Documents, Bid and Negotiation Process, Work Execution (Chapter 1.2)
Selection of repair work	General, Health and Safety, Structural Factor, Environmental Factor (Clause 5.3, EN 1504-9)	General, Health and Safety, Structural Factor, Environmental Factor (Application of Fundamental Principles of EN 1504)	Current Load Distribution, Compatibility of Repair Materials, Creep and Shrinkage, Vibration, Water and Vapor Mitigation, Material Behaviour (Chapter 1.2.2)
Fundamental principle	Principle 1 to 6 (Concrete Defects), Principle 7 to 11 (Reinforcement Corrosion) (Clause 6.2, Table 1 and 2, EN 1504-9)	Application of Protective System According to the Principle 1-8 and 11 from EN 1504	Not Applicable
Concrete removal and surface preparation methods	Not Applicable	Not Applicable	Advantages, Limitations, Features
Method of reinforcement repair	Not Applicable	Not Applicable	Advantages, Limitations, Features
Bonding process and material	Cementitious or Polymer Modified Materials	Not Applicable	Epoxy, Latex Bonding, Modified Epoxy Bonding, Cement-Based Bonding

3.3 Case Study 1: Irrigation Control Structures

Kubang Haji Irrigation Scheme involved in channeling water supply from Sungai Perak through 14 kilometers long of earth canal to 3000 acres of land in Perak state. Along the canal, there are seven irrigation control structures constructed with identical structural layout. Every control system consists of a triple rectangular culvert paired with several inlet stilling chambers to direct the water flowing through the culverts before reaching the downstream area. The water supply in the chambers is further split up by the sluice gates to regulate the water level especially during raining season (see **Fig. 2.**). The dimensions of the rectangular culverts are square section of 1.5 meter and approximately 8 meter long.

Fig. 2. Chamber with rectangular box-typed inlet controlled by sluice gates.

Out of seven, three irrigation control structures were experiencing heavy damages caused by abrasion effect and water erosion. Some sections of the reinforcement system and sluice gates were badly corroded as a result from pro-long soaking below the water level. Most of the structural damages were located at the adjacent areas of entry and discharge point of continuous water flowing.

In general, small volumes of surface preparation are preferred to apply an impacting method. According to Table 3.2.4 in ACI 546R-14, limited volume of concrete removal is suitable to use hand-held breakers among the impacting methods. Besides that, hand-held breaker is more preferable compared to boom-mounted breakers since boom-mounted breakers tend to do damage on remaining reinforcement and concrete during removal process.

The application of hydro demolition method in larger cleaning volumes of reinforcement system and concrete surfaces are recommended in all of the codes. Annex A.7.2.4 stated the cleaning operation by using high-pressure water jetting of 60 MPa to 110 MPa when there is a limited supply of water [3]. ACI 546R-14 further supported the usage of hydro demolition since the high-pressure water is able to clean the exposed reinforcement surface without damaging it or causing microcracks. In addition, creation of rough and irregular concrete surface profile from high-pressure water jetting is very efficient. Suggested by EN 1504 and SA HB 84:2018, contaminated concrete caused by flaky rust deposits on the surface of reinforcement system should be removed by high-pressure water jetting up to a minimum distance of 20 mm.

There are some approaches to recover the mechanical abrasion especially surface of the partition wall in the culverts and chambers. The relevant principles provided are Principle 1, 2, 5, 6 and 8 (surface protection system) [3]. EN 1504-9 further recommended hydrophobic impregnation, impregnation, or coating systems on the damaged surfaces of hydraulic structures [5]. For vertical and horizontal components of the chambers, selection of repair materials can initiate with injection of grouting into the cracks before the application of overlay materials. ACI 546R-14 provides sealer, membranes, and overlays as some surface treatments for protection against ingress, moisture control, physical or chemical resistance and increasing resistivity of the damaged components of the chamber [6]. Among the surface treatments, polymer concrete or polymer-modified concrete overlays are suggested for treating the surface areas of the chambers. This is because overlay materials provide rapid curing characteristics which cannot be achieved by using surface sealers or coatings. Added to that, polymer concrete overlays are also applicable to abraded partition wall of the culverts.

When dealing with chloride attacks, corroded steel gates are required to reinforce with either corrosion resistance products or conventional steel types. In this case, entire gates should be replaced by stainless steel gate or stainless-steel-clad gate. Commonly, Grades 304 and 316 are the favourable choices of selection [6].

Apart from that, treatment of corroded reinforcement system can be classified into Principle 4,7,8,9 and 11 in EN 1504-9. Annex A.8.3.1 recommended protective coating system in controlling the potential anodic area as defined in Principle 11. In order to restrict the oxygen molecules and chloride ions from accessing the reinforcement system, SA HB 84:2018 and ACI 546R-14 suggested to apply any cementitious, or epoxy resin coating materials on the exposed steel bars. In such case, epoxy based polyurethane system is suitable for coating of the reinforcement system with minimum thickness layer of 10mm based on EN 1504 [5]. The damaged reinforcement caused by loss in cross-sectional area is required to cut out and replace with mechanical connection or welding.

For the finishing layers, the entire irrigation control structure is recommended to apply render system mixing with cementitious coatings. The layer acts as an outermost protection barrier with anti-carbonation properties. SA HB 84:2018 further outlined polymer-modified renders as the protective system to limit the moisture attack [7].

3.4 Case Study 2: Low Cost Apartment Building

This building is named as Pangsapuri Taman Suria Pendamaran, located at Port Klang city. It is under the category of a low-cost reinforced structural building and was completed in 1998.

There was severe cracking on the wall panel in between the corridor and master room of the units extending from second to fourth floor of Block C (see **Fig. 3.**). In addition, location of cracks is quite difficult to be reached even with ladders. Corrosion situation of reinforcement system was unclear with the correlation of crack wide and movement. Nevertheless, the situation was considered much favorable as the crack development only ran through vertically. The panels showed no sign of concrete degradation.

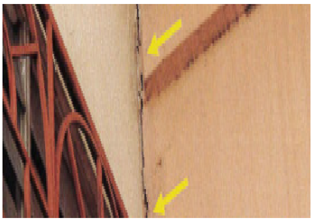

Fig. 3. Huge cracks can be seen at second floor of the Block C.

Next, spalled concrete was found on the soffit of the stair at third floor of Block C (see **Fig. 4.)** and surface of column member as shown (see **Fig. 5.)** Spalling occurred as a result from expansion of steel bars after corrosion effect. If the situations left untreated, relevant structural members may not be able to fulfill the minimum load capacities. Moreover, corrosion conditions of the reinforcement system will further be triggered by water from higher floors.

Finally, there were growing signs of moss and plant on the interior surface of corridor beam members in Block C (see **Fig. 6**).Water collection may appear every time after rainfall. Since there was no detection of any cracks or spalling, growing of mold on the beam surfaces were most likely in relation to the failure of water proofing system [8].

Fig. 4. Spalled soffit at third floor staircase of Block C.

Fig. 5. Corrosion of exposed reinforcement system due to spalling of the column member at ground floor.

Fig. 6. Detection of moss due to water ponding.

In the past, there were few repair attempts with polyurethane materials at the cracks on the surface of wall panels. The reappeal of cracks were in relation to ineffective of applied sealant after exceeding the durability years. According to Clause 8.2.6 in EN 1504-10, treatment of cracks should be based on Principle 1 and 4. Crack width and surrounding concrete surface are required to be maintained in a clean and dry condition. Injection of chemical grout is appropriate compared to soaking, filling, or vacuum techniques to fill the cracks from second floor and above. Chemical grouts can be grouped into rigid, or gel types [6]. In this case, filling the cracks between the panels are excellent with rigid type of chemical grout. Annex A.8.2.6 mentioned that low viscosity epoxy resin materials are able to fill in the fine cracks up to 0.1 millimeter, besides SA HB 84:2018 and ACI 546R-14 further specified the crack width up to 0.05 millimeter. Injection techniques should involve drilling holes along the crack surfaces before inserting the entry-port to pump the high-pressure injection. The scale of filling the cracks is available in Test or observation 33 in Part 10 [5].

For spalling situations, reinforcement system detected a mild signal of rusts. Cleaning and preparation of reinforcement system may not be necessary to remove the additional concrete layers or fully uncover the reinforcement circumferences. Upon the cleaning process, rough surface profile should be obtained around the spalled areas of column and soffit. In such case, materials for restoring concrete volume after spalling are cementitious mortar or polymer modified materials, following by bonding agent such as copolymer resins, epoxy or acrylic compound. In selection of polymer modified material or cementitious repair mortars, elastic modulus is required to have a minimum of 65 percent when compared to the elasticity of substrate concrete. Similarity, EN 1504 and SA HB 84:2018 suggested the pre-wetting of substrate surface before the application of primer (bonding agent) and any polymer-modified mortars. Generally, the typical thickness of patching works should be at least 25 millimeters, while epoxy-based mortar should be in 15 millimeter maximum. During the curing process, it is recommended to secure the repaired surfaces with polythene sheets on the column or spaying a layer of membrane at the soffit.

Lastly, failure of water proofing system at the flat roof can be classified into Principle 2, Moisture Control in EN 1504. Method 2.1 and 2.3, which are hydrophobic impregnation and over cladding introduced in Principle 2 but also applicable for Principle 8. Typical materials involved as hydrophobic impregnation are silanes, siloxanes, epoxy resin and polymer modified cement composition. These materials are suitable to resist the water penetration to lower sides of roof of Block C [7]. To restore the water proofing system against moisture attack and water diffusion in future, spraying of hydrophobic impregnators on the flat roof is preferred [3]. Also, covering the existing flat roof system with overcladding panel is another cost-effective way. Overcladding panel is able to protect the hydrophobic impregnators, as well as improving aesthetical value and thermal insulation of Block C.

4 Conclusion

Some conclusions can be drawn based on the study as follows:

According to the 11 principles listed in EN 1504-9, concrete damages are classified as concrete defects and corrosion on reinforced concrete structure. The SA HB 84:2018 is using the fundamental principles of EN 1504 as the main reference. However, ACI 546R-14 offered an extensive information on repair materials for certain protective systems, ranging from cementitious, polymer, bonding, and coating materials. In addition, strengthening processes are further classified into internal or external of concrete members and reinforcement system.

Similarly, all three codes agreed that the prime reason for concrete damage is reinforcement corrosion. The main difference between ACI 546R-14 and EN 1504 is that ACI 546R-14 does not provide any principle for all intended uses in repair works. The ACI 546R-14 discusses an extensive information on repair materials while EN 1504 gives priorities to quality control in performance of system and product applications.

Case studies of concrete structure repairing for irrigation control structures and low-cost flat building are discussed. In the first case study, heavily corroded reinforcement system and sluice gates were replaced. The entire abraded surfaces of the irrigation control structure were repaired by overlay materials. It is done before the application of render system that is mixed with anti-carbonation barrier. Whereas in the second case study, it was suggested that the cracking problem should be filled with chemical grout. On the surface of flat roof, hydrophobic impregnators and panel system were installed to prolong the water proofing system. In conclusion, the case studies reveal that it is possible to combine the strengths of a selected standards in reinforced concrete structures repair works.

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