Structural rehabilitation of columns with reinforced concrete jacketing

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Summary

Strengthening and rehabilitation by reinforced concrete jacketing of columns is assessed, considering different practical aspects: anchoring and slab crossing of the added longitudinal reinforcement, interface surface preparation, spacing of added stirrups, temporary shoring of the structure and addition of new concrete. Recent research on these topics and the main recommendations to achieve good RC jacketing are presented.

Key words: RC jacketing; strengthening method; structural rehabilitation; structural repair; retrofitting technique

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Introduction

Structural rehabilitation represents an important aspect of the construction industry and its significance is increasing. Several methods are available, each with different advantages and handicaps. However, little information is available and insufficient code guidelines are accessible. In fact, most repair and strengthening designs are based on the assessment of engineers only and, often, empirical knowledge and current practice have an important role in the decisions to be made.

The objective of this paper is to review one of the most commonly used retrofitting techniques: jacketing of reinforced concrete columns (Fig. 1). This method is evaluated according to different characteristics and, in order to help structural engineers to choose the most appropriate solutions, recommendations are given, based on published experimental research and real case studies.

When, why and how to rehabilitate a structure

When

The need to rehabilitate a structure may arise at any time from the beginning of the construction phase until the end of the service life. During the construction phase, it may occur because of

- design errors;
- deficient concrete production;
- bad execution processes.

During the service life, it may arise on account of:

- an earthquake;
- an accident, such as collisions, fire, explosions;
- situations involving changes in the structure functionality;
- the development of more demanding code requirements.

Why

The decision to rehabilitate must be made only after the inspection of the structure, its structural evaluation and a cost/benefit study of the different solutions. Rodriguez Park[1] published extensive bibliographic research on the repair and strengthening of RC structures in seismic areas such as the Balkans, Japan, Mexico, Peru and the USA. As an example, and related to the cost/benefit analysis, according to the authors, some buildings in Mexico City, repaired and strengthened after the 1985 earthquake, had a value between three and four times the operation cost.

How

The choice of the repair and/or strengthening method depends on the structural behaviour objectives.

In 1981, Sugano[2] published research on the seismic retrofit of buildings in Japan, based on rehabilitation procedures followed after 1968 in Tokachi-oki. According to the author, the goals of the strengthening strategies may be divided into increasing the resistance to lateral loads, improving the ductility, and an association of both. Basically, the

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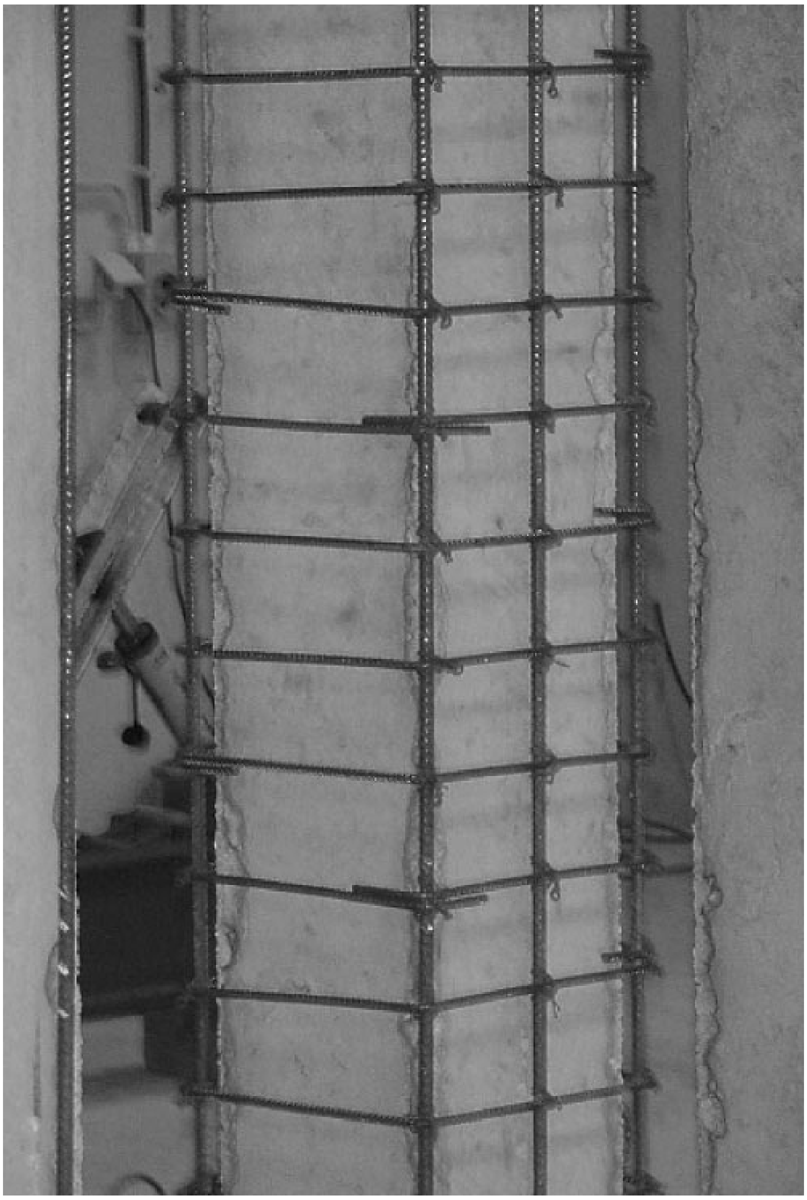

Fig. 1 Jacketing of RC columns

strengthening techniques for reinforced concrete structures can be divided into:

- addition of new structural elements;
- strengthening of the existing structural elements.

In 1989, Aguilar *et al.*[3] performed a statistical study on the repair and strengthening methods of 114 RC buildings damaged after the 1985 earthquake in Mexico City. According to this work, the most commonly used techniques were the addition of shear walls and the RC jacketing of columns.

Repair, Strengthening or both

REPAIRING A RC ELEMENT

Repairing a RC element may be defined as an attempt to restore the original strength and stiffness of a damaged or deteriorated RC element. Ramirez *et al.*[4] published an experimental study on repair of RC columns, where an interesting distinction between cosmetic repair and structural repair is introduced. The authors consider cosmetic repair if the strength loss is lower than 10% and structural repair if the strength decrease is above that value[4]. Following this concept, repairing RC elements, by just replacing some of the original materials, is acceptable only in the case of cosmetic repair since it does not restore characteristics of the original element.

Hellesland & Green[5] performed an experimental study on repaired RC columns. All models were first submitted to a complex loading history, consisting of a sustained load period, followed by a cyclic load period and finishing with a brief, deformation-controlled, loading to maximum capacity and beyond[5]. The models were repaired by straightening the columns, chipping out concrete from the failure zone, replacing old stirrups and adding new stirrups

in this zone and placing new concrete. The authors state that the load capacities of the repaired columns were found to be 15–20% less than the original load capacities, and the stiffness values were 50–90% of the original values.

STRENGTHENING A RC ELEMENT

Strengthening a RC element may be defined as an intervention to increase the original strength and stiffness of the RC element. In the case of an undamaged element, there can not be, by definition, a need to repair the element. In this case, there can only be a need to strengthen this element, due to one or more causes previously referred to.

REPAIRING AND STRENGTHENING A RC ELEMENT

In the case of a damaged and/or deteriorated RC element, strengthening must be associated with structural repair. The strengthening process must be preceded by the repairing operation. The importance and the cost of the latter depend exclusively on the structural hypotheses, assumed by the designer, relatively to the contribution of the original element to the strength of the resulting composite element.

Jacketing procedure of RC columns step by step

SYNOPSIS

This strengthening technique, unlike other methods where steel elements are used, does not have a specialized work demand. Its simplicity of execution makes any construction company, capable of building with quality new RC structures, also competent to execute structural rehabilitation using RC jacketing.

In the following paragraphs, this method is assessed according to different aspects: anchoring and slab crossing of the added longitudinal reinforcement, interface surface preparation, spacing of added stirrups, temporary shoring of the structure; and addition of new concrete. The current practice is analysed, published experimental research and real case studies are referred to and recommendations are given.

ADDED LONGITUDINAL REINFORCEMENT

Anchoring to the footing

One advantage of RC jacketing strengthening is the fact that the increased stiffness of the structure is uniformly distributed, in contrast to the addition of shear walls or steel bracing. In fact, for these procedures, it is usually necessary to execute new foundations or, at least, to strengthen the existing ones. Generally, in the case of RC jacketing, the steel longitudinal reinforcing bars of the added jacket can be anchored to the original footings.

Although there are several commercial products, very effective to bond the added steel bars to the RC footing, attention must be taken when executing this operation. Actually, the quality of the bonding can only be ensured if some details are considered.

Júlio[6] performed tests on RC columns strengthened by jacketing. The steel bars of the added longitudinal reinforcement were anchored to the footing of the original column by a commercially available two-component epoxy resin. The models were submitted to monotonic tests, consisting of a constant axial force combined with an increasing bending moment and shear force. Initially, failure of all steel bars of the longitudinal reinforcement of the original column and slipping of all the corresponding steel bars of the added jacketing were observed (Fig. 2). Pull-out tests were performed to analyse the problem and it was concluded, without any doubt, that the bars slipped because the holes drilled on the footings had not been adequately cleaned[6]. The use

Fig. 2 Failure of steel bars of the column and slipping of steel bars of the added jacketing

Fig. 3 Slant shear specimens prepared by sand-blasting

of a vacuum cleaner was enough to guarantee the change from slipping failure to tension rupture of the added steel bars.

Crossing the slab

When continuity between floors of the RC jacketing is required, holes must be provided in the slab to allow the longitudinal bars of the jacket to pass through. Alcocer[7] indicates that the use of column-distributed reinforcement (rather than column bundles) is appropriate to reduce the possibility of bond damage. In the case of slab–column structures, this procedure is easy to perform and has no drawbacks. In the case of beam–column structures, to avoid interrupting the middle bars, the longitudinal reinforcement must be located at the corners, which can lead to excessive bundling of bars[8] (Fig. 3). However, this technique can be implemented only with the objective of increasing the column shear strength and ductility and, in this case, gaps should be provided.

Hayashi *et al.*[9] performed an experimental study to quantitatively understand how mortar reinforced with welded wire fabric increases the shear strength and ductility of an existing RC column. Four types of test specimen were designed: (1) a non-strengthened specimen to serve as reference; (2) and (3) two columns strengthened with 4.5 cm-thick mortar and welded wire fabric lapped in different locations relatively to the loading direction; and (4) one column strengthened with 9.0 cm-thick mortar and welded wire fabric[9]. At both ends of the strengthened models, 3.0 cm gaps were considered. The experimental results revealed that the non-strengthened column deteriorated at a relatively early stage before the tensile reinforcement bars yielded; all strengthened models showed deterioration of load capacity when tensile reinforcement yielded before maximum load[9]. It was concluded that this strengthening technique increased shear strength and ductility, protecting the column from brittle shear failure.

INTERFACE SURFACE TREATMENT

Introduction

All published work on RC jacketing refer to the importance of interface preparation to achieve a good bond between the original column and the added jacket so that the resulting element behaves monolithically. The current practice in several countries consists in increasing the surface roughness of the original column, followed by the application of a bonding agent. In some cases, steel connectors are also considered.

Increasing surface roughness

Several methods are used to increase the roughness of the interface surface: hand chipping, sand-blasting, jack-hammering, electric hammering, water demolition, iron brushing, etc. Several authors state that increasing the roughness of the interface surface is necessary, but its influence has not been quantified[10–13].

There is also some published work on bonding of repair materials to a concrete substrate where preparation of the interface surface with different techniques is studied. One important unanimous conclusion is that pneumatic hammering causes micro-cracking of the substrate[14–17]. This technique is commonly used to increase the interface roughness, but should be avoid since it has been proved that the mechanical action of the hammer weakens the joint.

Júlio *et al.*[16–18] studied the influence of the interface between concrete layers of different ages on the strength of the joint. The authors performed slant shear tests and pull-off tests on specimens with the interface surface left as cast, prepared by sand-blasting (Fig. 3), prepared by electric hammering and treated with iron brushing. The authors state that

Fig. 4 Epoxy resin application on slant shear specimens prepared by sand-blasting

sand-blasting was the most efficient roughening technique of those considered[18].

Surface pre-wetting

The question of pre-wetting the interface surface is controversial. Even in codes and guidelines contradictions are found on this subject: the AASHTO-AGB-ARTBA Joint Committee recommends that the new concrete be cast on a dry concrete surface (except on hot, dry summer days) and the Canadian Standards Association standard A23.1[16] recommends wetting the old concrete surface for at least 24 h before the new concrete layer is cast.

Published experimental research[6,16,19,20] on this subject is not conclusive. However, according to Emmons[21], the moisture level of the substrate may be critical to achieve a good-quality bond. This author indicates that an excessively dry substrate can absorb too much water from the repairing material, causing excessive shrinkage. Excessive humidity on the substrate can close the pores and prevent the absorption of the repairing material. A saturated substrate with a dry surface may be considered the best solution.

Application of bonding agents

There are some published works on adhesion between repair materials and concrete substrates with bonding agents[16,20–22]. The conclusions reached by different authors are not always the same[16,20]. Furthermore, the results are not comparable, owing to the enormous variability of parameters that influence the interface strength.

Júlio *et al.*[18] performed slant shear tests and pull-off tests on specimens, considering different interface surface situations, previously referred to, and also considering the application of a commercial two-component epoxy resin (Fig. 4). The values of the shear and tension strength of the interface reduced when the epoxy resin was applied on the sand-blasted surfaces, contrarily to what happened when other roughening methods were used.

Addition of steel connectors

The use of steel connectors is of extreme importance in the case of precast RC beams with *in situ* cast slabs. Several publications[23–29], including codes and standards[18,30–33], deal with this subject.

Júlio *et al.*[6,18] performed push-off tests to analyse the influence of applying steel connectors on the interface strength (Fig. 5). Seven different types of interface surface preparation were considered. It was concluded that adding steel connectors crossing the interface did not significantly increase the debonding force, but increased almost directly the longitudinal shear strength considering slipping; the two commercial products used to anchor the steel connectors proved to be efficient; the fact that steel connectors were added after and not before the substrate was cast did not reduce the joint strength[18].

Synthesis

Júlio[6] performed monotonic and cyclic tests on undamaged RC columns strengthened by jacketing, considering different treatments of the interface surface. Six situations were considered in each set of tests: a non-strengthened column; a monolithic model; a column strengthened without any interface surface preparation; a column strengthened after the interface surface had been treated by sand-blasting; a column with the same roughness treatment as the latter and with added steel connectors; and a model where non-adhesion between the original column and the added jacket was artificially induced. Except for this latter situation, all models behaved monolithically when submitted to both monotonic and cyclic tests[6].

The major conclusion contradicts the current practice in several countries: for the conditions assumed, or more conservative ones (bending

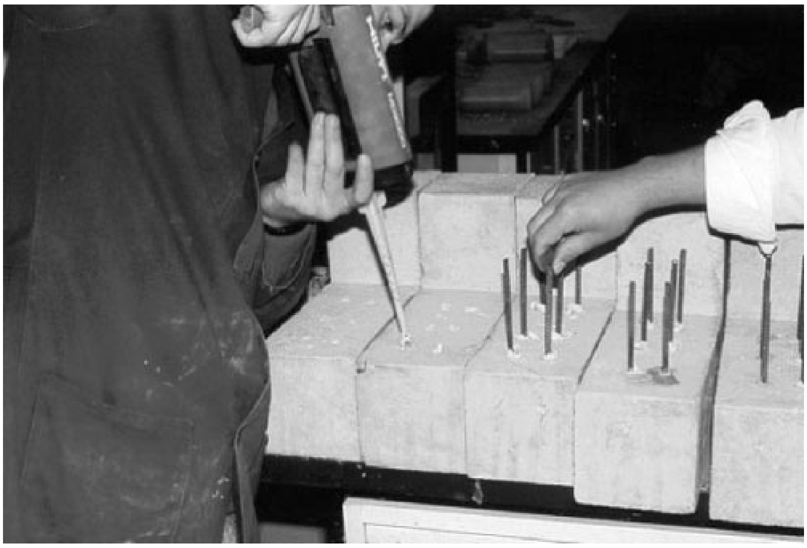

Fig. 5 Steel connectors epoxy bonded on push-off specimens

moment/shear force relation greater than 1 m) there is no need to improve the interface surface roughness nor to use any kind of bonding agent[6]. The author points out that this conclusion is valid for undamaged columns only. The author also performed a numerical analysis of the problem and concluded that, for short columns, there is a high probability of debonding of the RC jacket.

Bett *et al.*[11] studied the effectiveness of different repair and/or strengthening techniques in enhancing the lateral load response of identical RC short columns. Three test specimens were constructed: (1) a square column which was repaired and strengthened after testing and re-tested; (2) a column, identical to the latter model, strengthened with a shotcrete jacket; and (3) a model identical to the latter with additional longitudinal bars at each midface and supplementary cross-ties inserted through holes drilled in the column. The authors considered that the specimen representing an existing column performed poorly under reversed cyclic lateral deformations exceeding 0.5% drift. Columns strengthened by jacketing were much stiffer and stronger than the original, non-strengthened column. The column repaired by jacketing performed almost as well as the strengthened columns. The additional longitudinal bars and supplementary cross-ties of one strengthened model did not significantly affect the column's stiffness or strength under monotonic loading, but it did improve the level of strength and stiffness under cycles of reversed lateral displacements exceeding 2% drift.

SPACING OF ADDED STIRRUPS

Gomes & Appleton[34,35] studied the influence of the applied axial force and of the confinement level considered on the cyclic behaviour of RC columns strengthened by jacketing. The coefficients of monolithic behaviour of each repaired specimen were evaluated. The principal conclusion presented is that the monolithic performance of jacketed RC columns can be achieved if a higher percentage of transverse reinforcement is considered in the repaired solution. The authors recommend that half the spacing of the original column transverse reinforcement be adopted for the jacket transverse reinforcement.

TEMPORARY SHORING OF THE STRUCTURE

One important aspect of any strengthening technique is how it is made. There can be a considerable difference between strengthening a loaded element and an unloaded one. In the first situation, the RC jacket will resist load increments only as long as the original column is resistant to these and to the loads already applied. In the second situation, the composite element, the original column and RC jacket, will together resist the total load.

If the structural solution, defined by the designer, is the second situation referred to, a temporary shoring of the structure must be previewed. The objective is to transfer the load installed on the column to this shoring structure, in order to execute the RC jacket of the unloaded column. This can be easily performed by means of hydraulic jacks.

ADDED CONCRETE

Normally the added concrete has a maximum aggregate dimension of about 2 mm because of the lack of space in the jacket. This is due to its diminished thickness associated with the volume occupied by the added steel reinforcement. It is also for this reason that a self-compacting concrete (SCC) is frequently used. Again, because of the reduced thickness of the jacket, a high-strength concrete (HSC) is usually used. These HSC are normally obtained with silica fume additions. For this motive, these HSC are also high-durability concretes (HDC) and

therefore called high-performance concretes (HPC). Finally, since the concrete of the substrate is generally much older than the added concrete, it is also advisable that the latter be a non-shrinkage concrete.

Júlio *et al.*[6,18] studied the influence of the added concrete mix on the strength of the interface between this and the existing concrete layer. The authors concluded that the interface strength increased with the nominal strength of the added concrete and that, when a HPC was used, the rupture mode changed from interface rupture to monolithic rupture.

As previously referred to, Júlio[6] also performed monotonic and cyclic tests on undamaged RC columns strengthened by jacketing, considering different treatments of the interface surface. Apart from the non-strengthened columns and the monolithic models, in all other models the concrete of the added jacket was a commercial grout with characteristics of a HPC and SCC (Fig. 6). No jacket debonding occurred in any of the models, exception, obviously, for that where non-adhesion was induced[6].

Structural Behaviour

CORRECTION OF STRUCTURAL BEHAVIOUR

With this rehabilitation method, a significant increase of strength and/or ductility can be achieved. This technique can consequently be used to achieve these objectives, but also to correct the overall behaviour of the structure.

Alcocer & Jirsa[12] studied the response of RC frames redesigned by jacketing. The specimens were tested applying a bi-directional cyclic loading. The authors have concluded that jacketing may change the structural concept from a strong beam–weak column to a strong column–weak beam concept. They state that, by jacketing the most damaged element, the column, the strength and the stiffness were 35 and 45%, respectively, of the values obtained with the redesigned undamaged structure. They also state that, with adequate confinement and a strong column, bundled column bars did not have a negative effect on the behaviour of the specimens.

EFFECT OF DAMAGE ON STRUCTURAL BEHAVIOUR

There is a considerable difference between strengthening a healthy column and a heavily damaged column. Depending on the original column damage and on the repair efficiency, the influence of this difference may or may not be significant.

Alcocer[7] states, in his experimental study on RC frame connections rehabilitated by jacketing, that, by jacketing the most damaged elements, the columns and joint, the strength at 2% drift and the stiffness at 0.5% drift were 63 and 52%, respectively, of the values obtained with the undamaged specimen.

Rodriguez & Park[10] performed simulated seismic load tests on damaged and undamaged RC columns strengthened by jacketing to investigate the increase of strength, stiffness and ductility achieved. The authors designed the columns according to the 1950s New Zealand code and concluded that these could have low available ductility. They state that the strength and stiffness of the columns repaired by jacketing were up to three times those of the as-built columns. They mention that, during quasi-static cyclic lateral loading tests, with imposed nominal ductility factors of up to 6, very good energy dissipation and only a small reduction in strength was observed. The authors also mention that the effect of previous damage and the different reinforcing details used, had no significant influence on the overall seismic performance of the jacketed columns.

Stoppenhagen *et al.*[13] tested experimentally the behaviour of RC frames with heavily damaged

Fig. 6 Concrete casting of the jacket

columns repaired and strengthened by jacketing. The damage was characterized by heavy shear cracking and spalling of the concrete in the window space between spandrel beams. The authors state that the lateral capacity of the strengthened frame was approximately five times the calculated capacity of the original frame. However, they indicate that the initial stiffness of the repaired frame was approximately equal to the stiffness of the original frame, owing to the bond damage of the beam longitudinal reinforcement caused by previous numerous cycles of loads[13]. The authors recommend, based on observation of crack patterns and stress gradients in the transverse reinforcement, that torsion due to eccentric location of the beams into the repaired columns should be considered in the design. They mention the transfer of failure mode from non-ductile shear failure of the columns observed in the original model to a ductile hingeing failure in the beams.

Conclusions

The RC jacketing strengthening method, unlike other techniques, leads to a uniformly distributed increase in strength and stiffness of columns. The durability of the original column is also improved, in contrast to the corrosion and fire protection needs of other techniques where steel is exposed or where epoxy resins are used. Finally, this rehabilitation procedure does not require specialized workmanship. All those reasons make RC jacketing an extremely valuable choice in structural rehabilitation.

The structural behaviour of a building rehabilitated by RC jacketing of the columns, like any other strengthening technique, is highly influenced by details. In this method attention should be paid to the following aspects:

- repair method of the original column—removing the concrete from the deteriorated zone by hand chipping, jack-hammering, electric hammering or any other method that causes micro-cracking of the substrate, should be followed by sand-blasting or water demolition techniques;
- interface surface preparation—in the case of an undamaged and sound element, there is no need to improve the roughness of the interface surface, except for the situation of short RC columns, where sand blasting or water demolition should be used;
- use of a bonding agent—a two-component epoxy resin is most commonly used. However, an effective method to increase the surface roughness, such as sand-blasting, is enough to enhance the interface strength, when justified. In this latter situation, the subsequent application of an epoxy resin can even produce the opposite result and therefore should not be used;
- application of steel connectors—this should be considered only in the case of short RC columns to improve the level of strength and stiffness under cyclic loading;
- temporary shoring—the implications of shoring the original column should be considered in such a way that the RC jacket will resist part of the total load and not only part of the load increments;
- anchoring of the added longitudinal reinforcement—holes have to be drilled on the footings and appropriately cleaned. The use of a vacuum cleaner is highly recommended. The steel bars can be efficiently anchored to the footing with a two-component epoxy resin;
- continuity between floors of the added longitudinal reinforcement—holes must be drilled in the slab to allow steel bars to pass through. However, if the only objective is to increase the column shear strength and ductility, continuity is not needed and gaps should be provided instead.
- position of the steel bars of the longitudinal reinforcement—these should be uniformly spread. If this is not possible, attention must be paid to avoid excessive bundling at the corners;
- added stirrups—half of the spacing of the original transverse reinforcement is recommended for the added stirrups to obtain a monolithic behaviour under cyclic loading. These should also be placed out of phase;
- added concrete—a non shrinkage concrete should be adopted with characteristics of a self-compacting, high-strength and high-durability concrete.

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