New and emerging technologies for retrofitting and repairs

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1. Introduction

To meet up the requirements of advance infra structure new innovative materials/ technologies in civil engineering industry has started to make its way. Any technology or material has its limitations and to meet the new requirements new technologies have to be invented and used. With structures becoming old and the increasing bar for the constructed buildings the old buildings have started to show a serious need of additional retrofits to increase their durability and life.

Many environmental and natural disasters, earthquake being the most affecting of all, has also produced a need to increase the present safety levels in buildings. The understanding of the earthquakes, world over, is increasing day by day and therefore the seismic demands imposed on the structures get revised frequently. Similarly, the design methodologies evolve with the growing research in the area of seismic engineering and certain popular old design philosophies, such as soft storey structures, are no longer considered acceptable for earthquake resistant design. Many of the existing lifeline structures were analyzed, designed and detailed as per the recommendations of then prevalent codes. Such structures, pose a need to undergo re-evaluation process, say, every ten years. Such structures frequently may not qualify to current seismic requirements and therefore, retrofitting of these structures is essential.

The retrofitting is one of the best options to make an existing inadequate building safe against future probable earthquake or other environmental forces. There are many other factors, considered in decision making for any retrofitting strategy.

The following are some reasons that may need retrofitting:

1. Building which are designed considering gravity loads only.

2. Development activities in the field of Earthquake Resistant Design (EQRD) of buildings and other structures result into change in design concepts.

3. Lack of timely revisions of codes of practice and standards.

4. Lack of revisions in seismic zone map of country.

5. In cases of alterations in buildings in seismic prone area i.e. increase in number of story, increase in loading class etc.

6. In cases of deterioration of Earthquake (EQ) forces resistant level of building e.g. decrease in strength of construction material due to decay, fire damage, and settlement of foundations.

7. The quality of construction actually achieved may be lower than what was originally planned.

8. Lack of understanding by the designer.

9. Improper planning and mass distribution on floors.

Many options for retrofitting a structure are possible; the ones which are used traditionally for a long time now such as Addition Of New Shear Walls, Addition Of Infill Walls, Addition Of Wing (Side) Walls, Addition Of Buttresses, Jacketing Of Reinforced Concrete Members, Propping up, Sleeving, Steel collars, Casing, Building up, Bonding Steel Plates or Steel Jacketing.

However, with increase in research and introduction of new materials and technology there are new ways of retrofitting the structure with many added advantages. Introduction of Fibre Reinforced Composites being one of them. It has proved to be a promising material and technology in repairs and retrofitting.

2. Recent Retrofitting Methods

There are many relatively new technologies developed for seismic Retrofitting which are based on "Response control". These techniques includes providing additional damping using dampers (Elasto-plastic dampers, friction dampers, tuned mass and tuned liquid dampers, visco-elastic dampers, lead extrusion dampers etc.) and techniques such as base isolation which are introduced to take care of seismic control.

Methods of Retrofitting

- Increase the capacity/strength of the system (Seismic Resistance Based Design) (i) Concrete Jacketing, (ii) Steel Jacketing, (iii) FRP Wrapping
- Reduce the demand/forces on the system (Seismic Response Control Design) (a)Elasto-Plastic Dampers, (b)Base Isolators, (c) Lead Extrusion Dampers, (d)Tuned Liquid Dampers, (e) friction dampers

The following steps are generally followed for retrofitting of structures:

1. Deciding the team for the project.

2. Gathering information on type of lifeline structures and construction.

3. Assessing the information on in-situ condition of the structure (Non-Destructive Examination).

4. Identification of systems for which the re-assessment is to be carried out.

6. Evaluating the requirements to be met by retrofit (e.g. codal requirements).

7. Developing and designing of retrofit.

Controlling seismic response in structure systems and components can be performed using active semi-active, passive dampers and seismic Base Isolators.

Following are the newly developed and used technologies for retrofitting of structures.

2.1. Elasto-Plastic Dampers

These are based in plastic deforming steel plates, consisting of X-shaped plates. These plates sustain many cycles of stable yielding deformation, resulting in high levels of energy dissipation or damping.

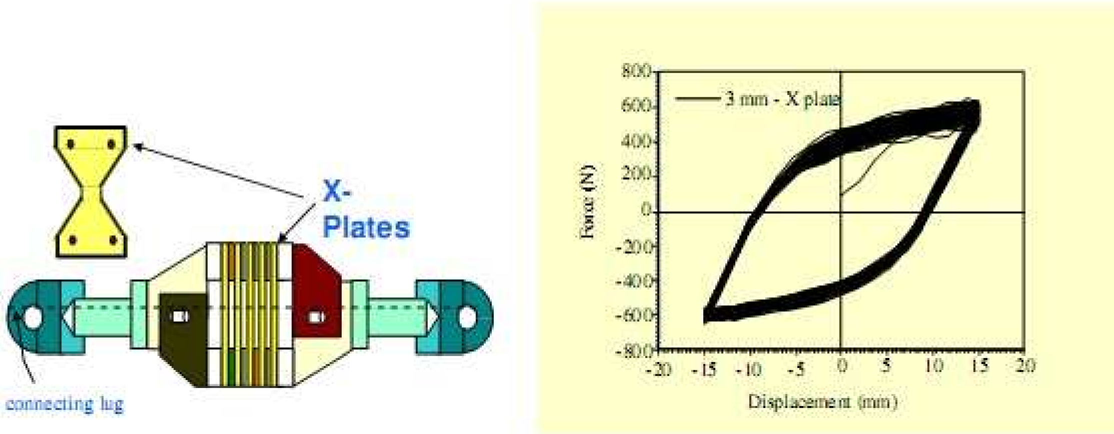


Fig 1 Elasto- Plastic damper and the hysteretic Charecteristic of the x-plate

A case study have been discussed in the Case Studies section of the paper about using the damper in a real structure and results

2.2. Tuned Liquid Dampers (TLDs)

TLDs are rigid walled containers filled with liquid up to certain height, to match the sloshing frequency and are placed at the rooftop of the structure. The Device absorbs vibration energy through liquid sloshing principle.

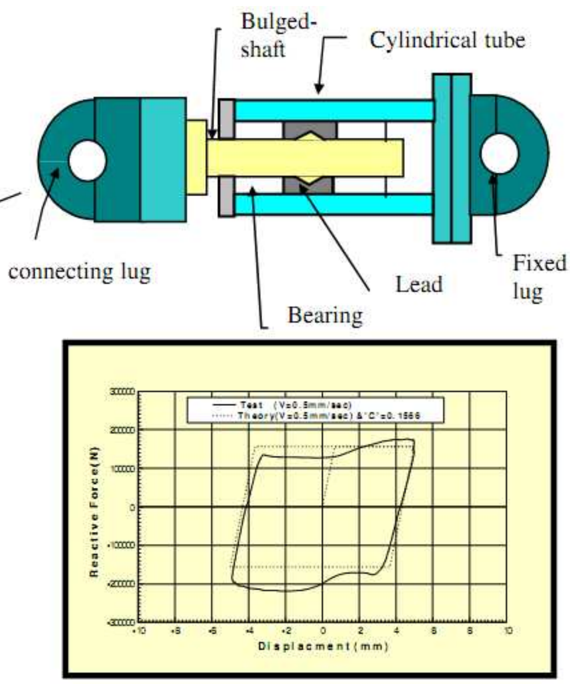


Fig 2 LED on a Test machine

Fig 3 The Structure and the Hysteric charecteristic

2.3. Base isolators

The base isolation is aimed to attenuate the horizontal accelerations transmitted to the superstructure. The isolators attempt to decouple the building or structure from the horizontal components of the ground motion. Isolators have low horizontal stiffness and they are placed between the structure and foundation.

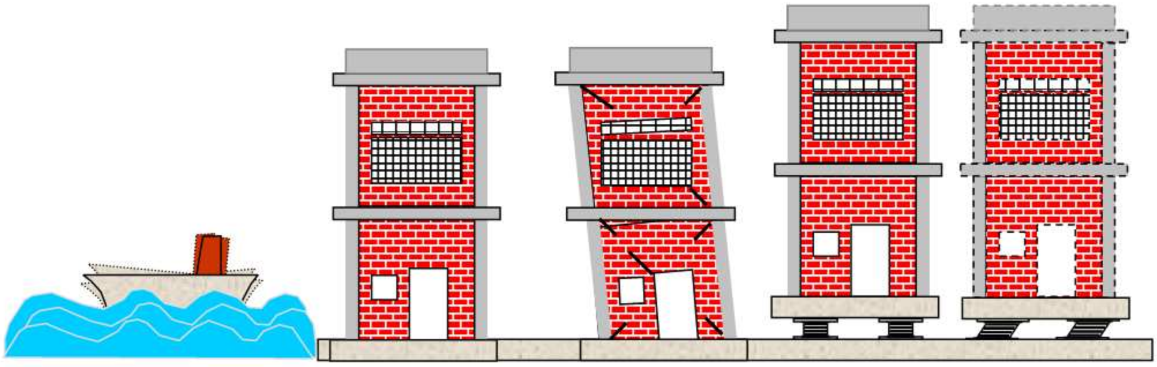


Fig 4. Principles of Base Isolation Technology

In the later part of the paper a case study on a base isolated structure in guwahati have been presented.

2.4. Non-Metallic Fibre Composites/Fibre Reinforced Composites (FRC)

Commonly used forms of FRC viz. Pre cured CFRC (Carbon Fibre Reinforced Composite), Glass Fibre Reinforced polymer Composites (GFRC) rebar, glass fibre roll, etc.

Fibre Reinforced Polymer (FRP) composites comprise fibres of high tensile strength within a polymer matrix such as vinylester or epoxy. FRP composites have emerged from being exotic materials used only in niche applications following the Second World War, to common engineering materials used in a diverse range of applications such as aircraft, helicopters, space-craft, satellites, ships, submarines, automobiles, chemical processing equipment, sporting goods and civil infrastructure. The role of FRP for strengthening of existing or new reinforced concrete structures is growing at an extremely rapid pace owing mainly to the ease and speed of construction, and the possibility of application without disturbing the existing functionality of the structure. FRP composites have proved to be extremely useful for strengthening of RCC structures against both normal and seismic loads. The FRP Composites

as shown in Fig 11 used for strengthening of RC structures can be mainly categorized as

(i) Laminates, for flexural strengthening

The laminates are generally made up of Carbon fibres blended in an epoxy matrix. These when applied with epoxy, act as external tension reinforcements to increase the flexural

strength of the RCC members.

The main advantages of Fibre reinforced composite laminates No corrosion, No transportation problem, High ultimate strength, High Young's modulus, Very good fatigue properties, Low weight and Endless tapes available so no joints.

Fig 5 Use of Laminates in for strengthening of slabs in a bridge and a building.

(ii) Fibre wraps, for shear and axial strengthening

Fibre wraps are made up of three different materials namely Carbon, Aramid and Glass. Carbon fibre is the strongest, most inert and the most expensive one; glass is the cheapest and has low elastic modulus and strength. Aramid fibre is used mainly for impact resistance. The concept of flexural and shear strengthening of RC beams using FRP composites is quite straight forward and exactly similar to the steel reinforcement used for normal RC construction. For flexural strengthening, the laminates act as longitudinal reinforcement and for shear strengthening, the wraps act as shear reinforcement (stirrups).

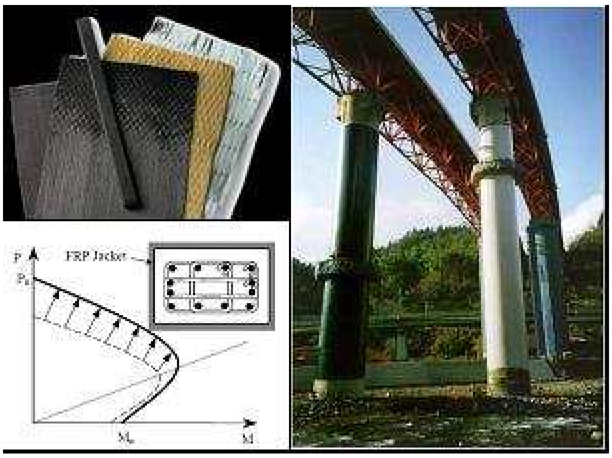


Fig 6. Different types and uses of Fibre wraps

3. Fibre Wrapping, An Innovative Retrofitting technology

Of the two forms of Fibre reinforced composites the FRP **Fibre wraps** have started becoming a widely accepted and industrially practiced technique of retrofitting structures. Different aspects of fibre wrapping are now discussed.

3.1. The concept

Involves wrapping of RC columns by high strength-low weight fibre wraps to provide passive confinement, which increases both strength and ductility.FRP sheets are wrapped around the columns, with fibres oriented perpendicular to the longitudinal axis of column, and are fixed to the column using epoxy resin. The wrap not only provides passive confinement and increases the concrete strength, but also provides significant strength against shear.

Confinement is generally applied to members in compression, in order to enhance load bearing capacity or, in case of seismic upgradation or, to increase their ductility in potential plastic hinge region. The Confinement in seismically active regions has proven to be one of the early applications of FRP materials in infrastructure applications. Confinement may be beneficial in non-seismic zones too, where, for instance, survivability of explosive attacks is required or the axial load capacity of a column must be increased due to higher vertical loads, e.g. if new storey's have to be added to an existing building or if an existing bridge deck has to be widened. In any case, confinement with FRP may be provided by wrapping RC columns with prefabricated jackets or in situ cured sheets, in which the principal fibre direction is circumferential. Beams, Plates and columns may be strengthened in flexure through the use of FRP composites bonded to their tension zone using epoxy as a common adhesive for this purpose. The direction of fibres is parallel to that of high tensile stresses. Both prefabricated FRP strips, as well as sheets (wet-lay up) are applied.

Shear strengthening is usually provided by bonding the external FRP reinforcement on the sides of the webs with the principal fibre direction perpendicular or with an angle of e.g. 45° to the member axis.

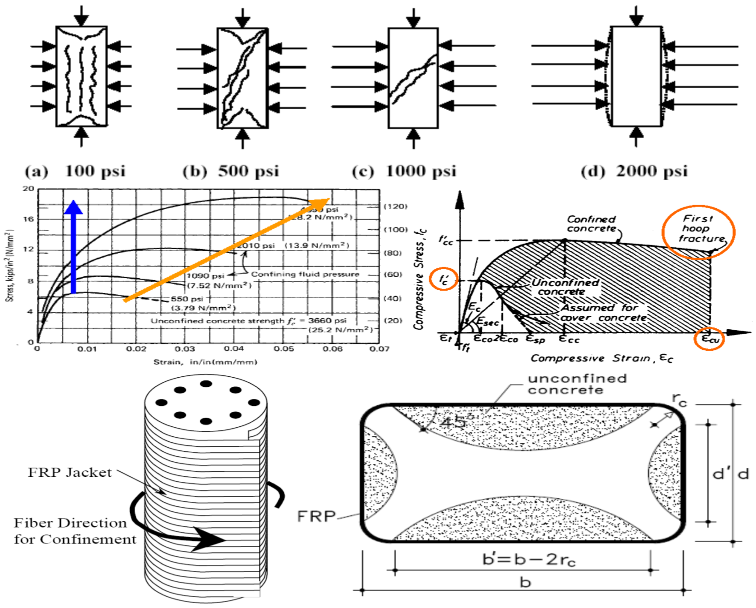


Fig 7 the Concept of Confinement

3.2. The concept strengthening of RC Columns by FRP Composites

As concrete is uniaxially compressed due to load, Poisson's effect induces transverse strains that result in radial expansion of the concrete.This increase in transverse strain results in volumetric expansion. By confining the concrete using a continuous FRP jacket, i.e. wrapping of RC columns by high strength-low weight fibre wraps to provide passive confinement, the fibres resist the transverse expansion of the concrete and provide passive confinement which increases both strength and ductility. FRP sheets are wrapped around the columns with fibres oriented perpendicular to the longitudinal axis of column, and are fixed to the column using epoxy resin.The wrap not only provides passive confinement and increases the concrete strength, but also provides significant strength against shear. Since, FRP jacket acts to contain damaged sections of concrete, the maximum usable strain level in the concrete is limited only by the ultimate strain obtainable in the FRP jacket and not by concrete crushing.To increase the effectiveness of wrap, the sharp edges of the rectangular sections must be rounded.

3.3. Design of fibre reinforced strengthening.

The design of FRP strengthening is performed on the well established principles of mechanics. Most major codes like ACI, CEB-FIP, EuroCode, Japanese code, Swedish bridge code, Chinese Standard,Turkish code etc give guidelines for the design of FRP system for wrapping of concrete columns to increase their capacity. Various institutes like NCHRP, Caltrans, CPWD etc recommend the use of FRP Composites for strengthening of concrete structures. For design of strengthening, a composite action is assumed between fibre and existing concrete. The design is based on following assumptions -

- No slip between FRP and Concrete.
- Shear deformation within adhesive layer is neglected.
- Tensile strength of concrete is neglected.
- FRP jacket has a linear elastic stress-strain relationship up to failure.

Fibre wrapping is done on RC members in following different ways

1. Strengthening of junction area by means of L-Wrap:- It is done at the the beam- column joint to strengthen the joint.
2. Strengthening the junction area by flat wrap:-
3. Strengthening of the junction area by means of U-Wrap.
4. Column confinement by fully covering the column or beam with fibre wrap.

In actual real life cases a mix of all these techniques is used to attain the designed strengthening requirements.

Confinement effectiveness of externally bonded FRP jackets depends on different parameters namely

- type of concrete,

- steel reinforcement,
- FRP jacket stiffness (type of FRP, number of plies and design of wrap),
- shape of cross section,
- radius of corners, for non-circular sections, and loading conditions.

Uniaxial compression tests on RC columns confined with CFRP jackets have shown that the increase of ultimate strength is highly influenced and increases with the radius of the corners of square sections. Hence it gives better results for columns with circular cross sections than those with Square/Rectangular cross- sections. For achieving better results in case for effectiveness of FRP confinement with Square/Rectangular cross-sections, the sharp edges are given some curvature to increase FRP wrap more effective.

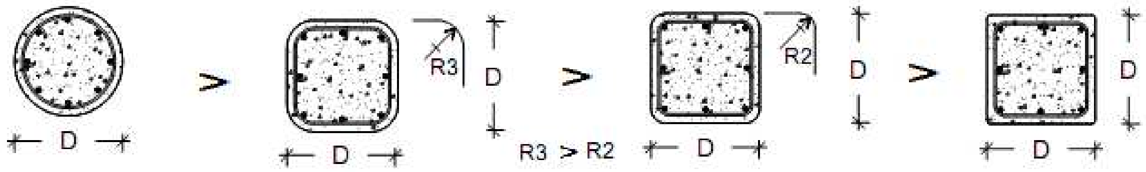


Fig 8 Comparison of Fibre Wrap effectiveness with curvature in the cross-sectional area.

3.4. FRP Composite Materials for Bridge Applications

The first pedestrian FRP bridge was built by the Israelis in 1975. Since then, others have been constructed in Asia, Europe, and North America. Many innovative pedestrian bridges have been constructed using pultruded composite structural shapes which are similar to standard structural steel shapes. Because of the light- weight materials and ease in fabrication and installation, many of these pedestrian bridges were able to be constructed in inaccessible and environmentally restrictive areas without having to employ heavy equipment. Some of these bridges were flown to the sites in one piece by helicopters; others were disassembled and transported by mules and assembled on site. The advancement in this application has resulted in the production of second generation pultruded shapes of hybrid glass and carbon FRP composites that will increase the stiffness modulus at very little additional cost. The recognition of providing high quality fibres at the most effective regions in a structural members cross section is a key innovation to the effective use of these high performance materials.

There is much work to be done in developing well-designed anchorages, connection details, and bonded joints in compsites for long-term durability. Bridge engineers are reluctant to rely solely on epoxy adhesive bonding technology to connect or join structural components. Electrical transmission towers out West have been built with connections that were snapped and locked together without the use of any fasteners. It is a tough challenge, but when adequate testing and performance data are available, bridge engineers will change their paradigm.

After the 1989 Loma Prieta earthquake, the California Department of Transportation mounted an extensive testing and development program to retrofit bridge piers using FRP composites. Having confirmed its performance in the laboratory, fibre wrap, filament winding, and pre-cured cylindrical half-shell systems were quickly developed, tested, and accepted as alternates to steel jackets for seismic retrofit of bridge piers in high seismic areas. Since then, thousands of concrete bridge piers that were designed with inadequate ductility, lap splices, and shear capacity have been successfully retrofitted using FRP composite wrap systems. The University of California at San Diego has determined that when a wrap system is properly designed and installed, the ductile capacity can be significantly increased to allow twice the deformation levels without any reduction in its capacity as compared to the as-built bridge piers.

These fibre wrap systems are also being used to repair deteriorated concrete piers, pier caps, and damaged beams. Under a small-scale research study, a damaged prestressed concrete girder was repaired with carbon fibre sheets. The repaired girder was tested to a higher capacity than that of the original girder. With this application, the condition of the deterioration in the concrete behind the composite materials remains uncertain. A good repair program should include an evaluation of the pre-existing condition and structural integrity of the concrete to establish a baseline reference. After a structural member has been repaired, the in-service condition of the concrete substrate as well as the performance of the composites should be continuously monitored.

3.5. Comparision between different types of fibres for use as wraps for strengthening

Comparison for choosing the best products is necessary. If economical factors are kept aside for some cases, it is found that carbon FRP have a lot of advantages over other types of FRP. This writeup aims in presenting the major points which makes Carbon –FRP a better solutions for design and execution.

The following are the reasons for Superior properties of Carbon- FRP than that of A-FRP and G-FRP

1. Modulus of elasticity: For the same Fibre Wt., the strength and Modulus of Carbon Fibre Wrap is far more superior than that of Aramid (75% higher) and Glass (150% higher).
2. The Design Strength is considerably higher for carbon than that of aramid and glass fibre wrap. The strains achieved are also lower in case of carbon. This gives a higher Design capacity and range with carbon fibre wraps for strengthening. Below is the graph showing the Design strength vs the strains developed in wraps of all kinds.

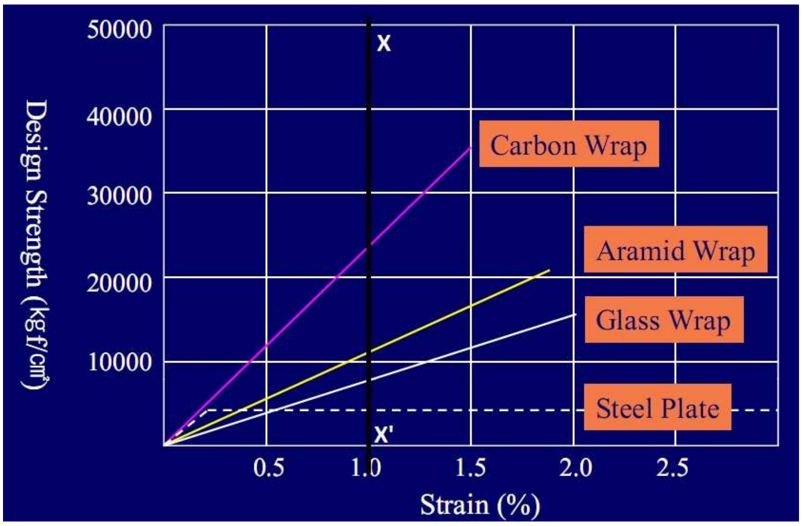


Fig 9. Graph showing Design Strength vs Strain Graph for all three Fibre wraps.

3. At the maximum design strength the modulus of elasticity is higher in Case of carbon than aramid and glass. This shows superior properties in carbon than the other two. This also show that carbon goes to a higher value of both modulus and design strength hence giving a sense of better material property and better design limit for carbon than the other two.

4. The durability with time of Carbon Fibre Wraps is far more better than that of Aramid and glass. There are two important points to be considered.

   a. Carbon does not show any loss in tensile strength in rapid Exposure test. Whereas both Aramid and glass loose there strength i.e. 35% and 30% respectively after 10000 hr of rapid exposure which is in principle equivalent to 30 years.

   b. Comparing the rate of deterioration Aramid fibre looses more than 80% of its strength in half of the time, whereas glass fibre deteriorates almost linearly. Showing better functionality of glass than aramid fibres.

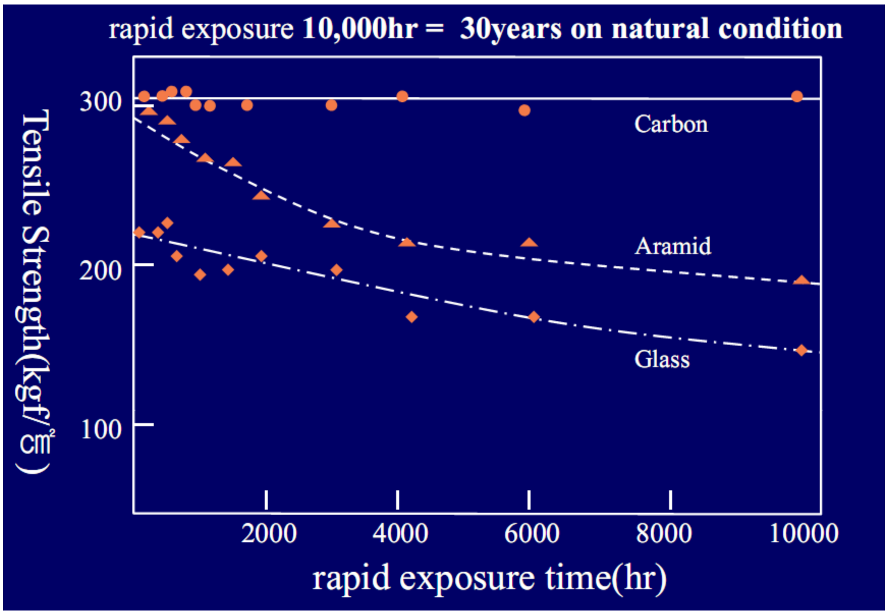


Fig 10. Graphs showing deterioration with time in rapid exposure test.

5. Comparing the fatigue Characteristics by cyclic loading of the fibre sheets. Again Carbon Fibre shows high performance than both aramid and glass wraps. For the same amount of stress carbon takes fairly high amounts of loading for failure. Fig 3 shows the fatigue characteristics of commercially available Fibre wraps.

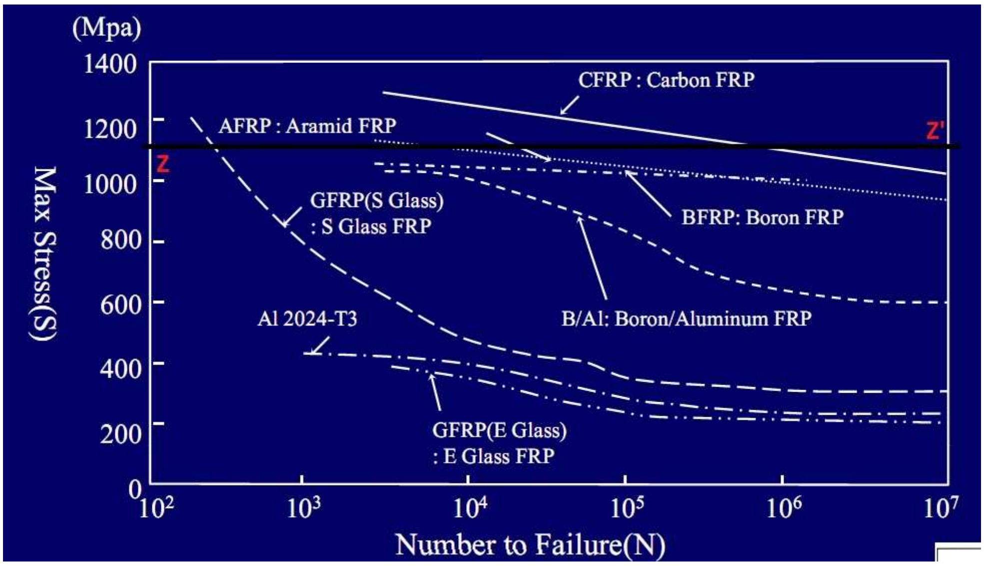


Fig 11. Graph showing fatigue characteristics of different fibres.

3.6. Challenges and Technical Issues

The main concern with FRP composites is long-term durability because the materials do not have sufficient historical performance data in bridge applications. There is a concern among bridge engineers for the long-term integrity of bonded joints and components under cyclic fatigue loading. There are concerns with improper curing of the resins and moisture absorption and/or ultraviolet light exposure of composites that may affect the strength and stiffness of the structural system. Certain resin systems are found ineffective in the presence of moisture. In the case of a glass fibre composite, moisture absorption may affect the resin and allow the alkali to degrade the fibres.

The high strength, high fatigue resistance, lightweight, and corrosion resistance of composites are highly desirable characteristics for bridge applications. Currently, these new materials are a direct technology transfer from the aerospace industry, and they are far more advanced than those required by civil applications. Most of the advanced composite materials that are cured at high temperature produce high quality components and possess excellent characteristics. In bridge applications, resins as the binders for the fibre and adhesives for joints and connections that can adequately cure at ambient temperature and still offer comparable quality and characteristics are more desirable and practical. More research is needed to develop the most effective and durable resin formulations. More efficient manufacturing and effective production methods for large volume panels and higher modulus materials are needed to make it more cost effective for composites to compete in the civil infrastructure. At the present time, the direct use of fibre composites from the aerospace industry is not cost effective as compared to conventional materials in bridge applications.

4. External Pre- Stressing using Fibre reinforced polymer.

We know the pre- stressing of concrete is a very effective way of using the high compressive strength property to much greater extend. Moreover, permenant deformations in the structure can be recovered by this technique. This technique of prestressing concrete is possible only in new structures.

The advantages of resistance to corrosion and high specific strength make these materials ideal for reinforcing existing structures with minimum intrusion. Popular method adopted is bonding them adhesively to concrete structures. However, we can seldom fully use the superior strength properties of these FRC's due to poor capacities of concrete and interfaces formed. Pre-stressing of these materials allow us to better utilization of its properties.

External Pre-Stressing is done in two ways

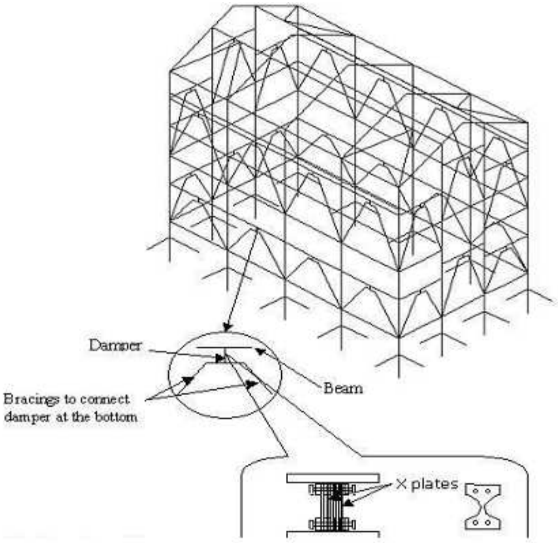
a. Using Fibre reinforced composite Laminates. This includes externally reinforcing beams and slabs from below with laminates giving the members extra flexural and shear strength. The Pre-Stressing gives the members an active upward force even when no live load is given.
b. Column Pre-stressing:- An innovative technique and machinery for retrofitting of columns and joints of a RCC structure have been developed by us. It involves confining of column with Carbon/Epoxy or Aramid/ Epoxy Composite-Belts and Pre-Stressing it so that it confines the column in stressed position. This is new and exclusive technique which enhances the capability of FRP to confine the columns.

5. Case studies

5.1. Seismic Retrofitting of APSARA Reactor Building

Seismic re- evaluation of APSARA reactor building at BARC, Mumbai was performed and it was found necessary to improve the capacity of building, especially in footings. To meet this, it was proposed that the building should be retrofitted with elasto- Plastic Dampers. Elasto- Plastic Dampers consisting of fifteen SS- 316 6 mm thich plates would be provided in the frames of the RCC building and the connections of dampers with the beams and columns of the structure were to be made using ISMC 125 box sections.

Seismic response of the building by Response Spectrum Method was obtained with seismic input motion pertaining to 7% damping of spectra shown in Fig. 26. The results of this analysis are presented in the Fig 27 (a), (b), (c) and (d).



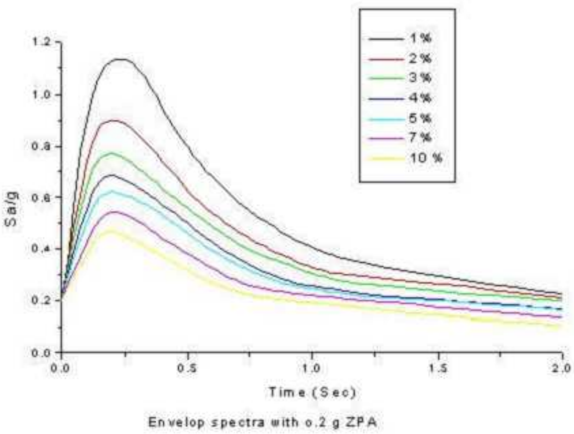


Fig 12 Location of Dampers

Fig 13 Response Spectrum

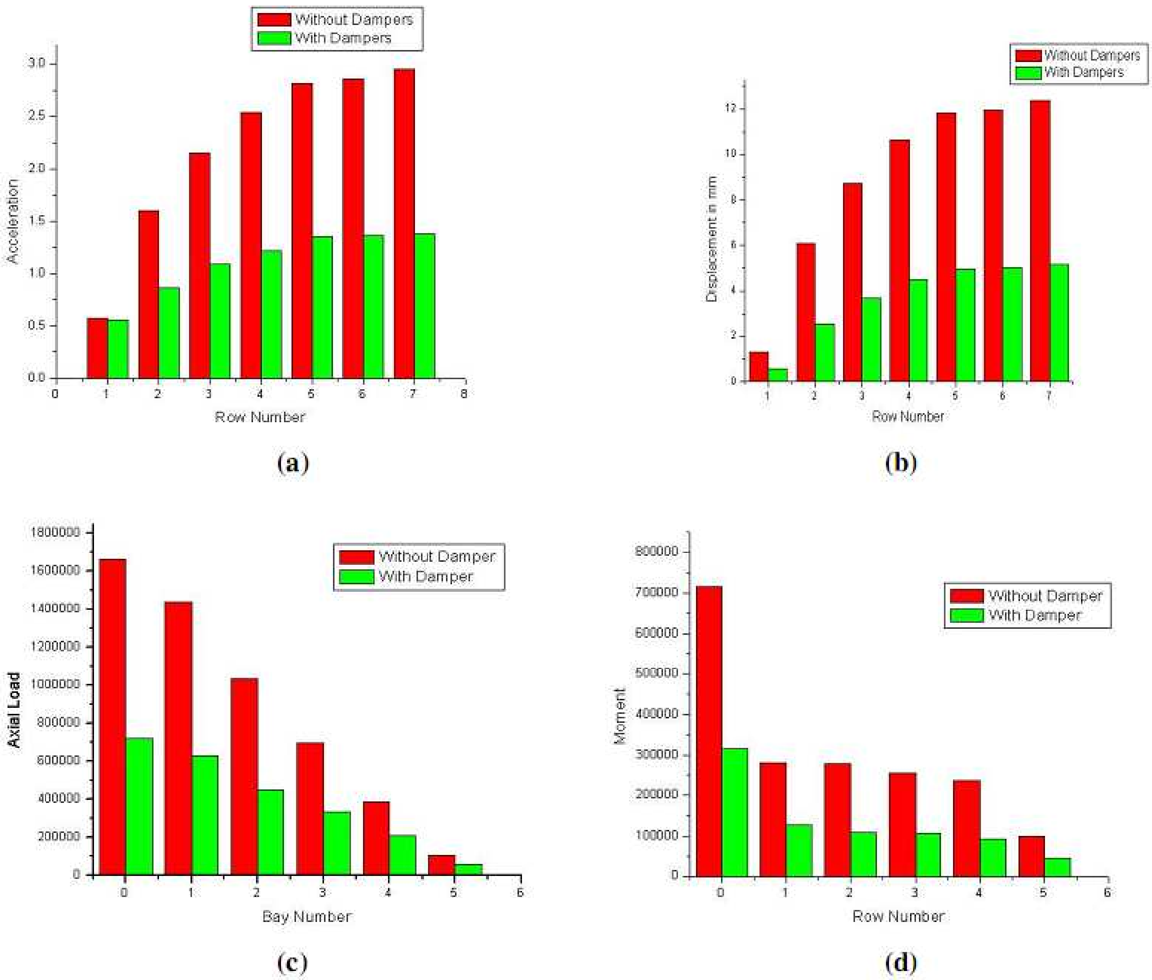


Fig 14 Comparitive Plots of Seismic Analysis.

5.2. Base Isolators used in a actual building

To study the behavior effectiveness of base isolation, two numbers of three-storeyed framed RCC buildings with similar construction, one building with conventional foundation (here onwards called as normal building) and other with base isolation as shown in Fig. 29, were built at IIT, Guwahati campus. Guwahati is situated in the most severe seismic zone (Zone-V) of Northeast India. Northeast India is lying at the juncture of Himalayan Arc to the north and Burmese Arc to the east, and is one of the most active regions of the world.

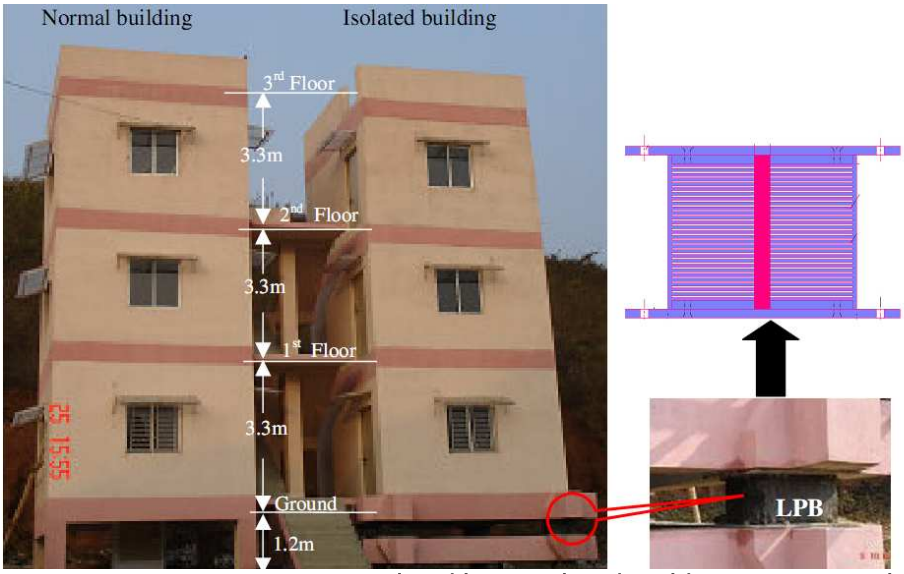


Fig 15 Normal and base Isolated Buildings at IIT Guwahati

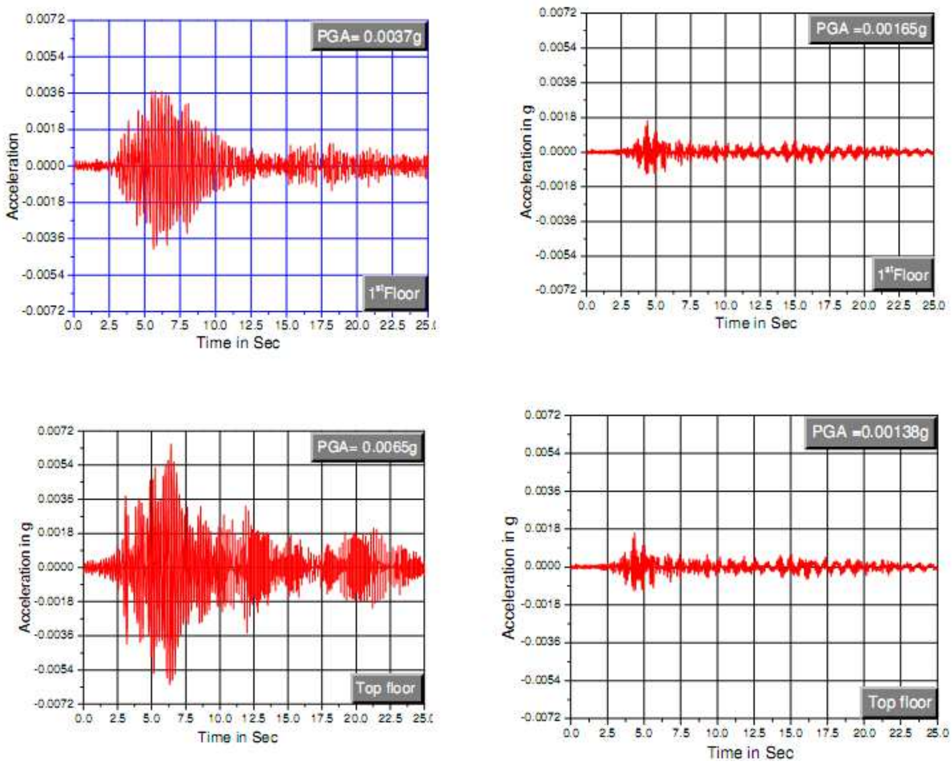


Fig 16 Response of Buildings subjected to actual earthquakes MAGNITUDE: 5.2, Nov 06, 2006, LOCATION: 24.736° N 95.223° E, DEPTH: 122.6 km

5.3. Gulraj Hotel, Mhape

In the construction Phase it was desired to add two extra floors. This caused design load changes which were to be made in the already constructed structure.

The column strength was enhanced by using Grooved Carbon –laminate(Because of rectangular columns and their large aspect ratio) and subsequently Fibre Wrapping them for enhancing the strength so that they can reach the new design loads.

Fig 17 Fibre Wrapping of Columns to increase load capacity to fulfill the increase in design loads.

5.4. Platina Wadhwa, Bandra-Kurla Complex

Due to change in usage and thereby causing redistribution of loads, the PT Slab came under critical condition. The strengthening of slab was done using Composite Fibre Laminates and external Pre-stressing using these composite Fibre laminates. The details are as follows:-

Strengthening of Slab from above i.e. **Negative Reinforcement of Slab and the ends area.**

Fig 18 Strengthening of slab from above using Carbon Fibre Composite laminate with anchor plates at the end

Strengthening of slab from below i.e. positive reinforcements by Pre-Stressing the below laminates using our technology for active support to the slab.

Fig 19 Strengthening of slab from below using the Pre-Stressed Carbon Fibre Laminates With anchor plates at the end

5.5. J W Marriot, Chennai

A change in floor load capacity of the existing structure due to change in loadings above the structure required it for slab strengthening .

The strengthening was done using Carbon –Fibre Reinforcement composite Laminates and FRP wrapping using Carbon fibre sheets.

Fig 20 Strengthening with Carbon Fibre Laminate system.

Fig 21 Strengthening of Columns and Joints using FRP Wrapping.

ESIC Hospital, Bangalore

50 years old structure needed a renovation to increase load carring capacity of its beams as new and latest equipments were installed in the hospital. Hence beam strengthening was to be done by External Pre- Stressing by carbon fibre Laminates.



Fixing of anchor plates and pre-stressing jack for External Pre-Stressing by Carbon Laminates.

6. References

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