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REVIEW ON STRUCTURAL STRENGTH ASSESSMENT OF EXISTING BRIDGES

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ABSTRACT: The present study provides a critical overview of the state-of-the-art existing reliability assessment of reinforced concrete bridges. The techniques were classified broadly as Inspection and maintenance, Assessment of condition, posting of bridges, rating of existing bridges, load testing and structural health monitoring. The study revealed various techniques and helpful information that could be employed for superior forecasting of the effective service life of degrading RC bridges as well as in predicting the optimum time for periodic inspection and creating maintenance strategies for continued service life of the bridges. This structural assessment guideline can be applied to all kind of existing bridge structures for all type of structural material (concrete, steel, timber, masonry, composite material). Experience based quantitative assessment of deterioration effects and other damage through visual inspection is carried out where as Serviceability based quantitative assessment of safety and reliability is carried out using refined model-based monitoring of static and dynamic test data.

KEYWORDS: Retroffitting, Structural Health Monitoring, Destructive and Non-Destructive testing.

1 INTRODUCTION

Bridges are considered as the key element in the present scenario of transportation system as they control the capacity of the traffic system. If the bridge fails, the system fails, hence it is utmost essential to strike balance between capacity and cost without compromising on safety. Reinforced concrete bridges constructed prior to 1971 have been designed with little or no ductility considerations and are particularly vulnerable to damage when exposed to a moderate earthquake. A bridge engineer has to keep in mind the future traffic volume, the heavier cost of construction and thereafter periodic or routine maintenance while working on bridge project.[4] Strength must always be of utmost importance, but at the same time measures should be taken to prevent deterioration. Functionality of bridges determines the efficiency of traffic movement on road. Reinforced concrete may also be permanently stressed (in compression), so as to improve the behaviour of the final bridge structure under working loads through pre-tensioning and post-tensioning. Failures of bridges have occurred ever since bridge building started thousands of years ago. A large part of the technical knowledge associated with bridge engineering today is based on the past failures of bridges. Based on past history, bridge failure can be categorised as under:

1.1 Natural factors

a) Earthquake: Earthquakes lead to vertical and horizontal ground motions that can result in the failure of bridges.
b) Wind: Forces and vibrations induced by wind leads to large displacements and stresses that may exceed the capacity of bridge structures and thereafter resulting in the collapse of bridges
c) Cyclone: The hydrodynamic forces caused by tropical cyclones cause severe damages in the bridges in coastal areas.
d) Scour: Scour is a phenomenon in which the level of the riverbed becomes lower under the effect of water erosion, leading to the exposure of bridge foundations. when the critical scour depth is reached, bending or local buckling of the foundation may occur under the combined effect of the dead load of bridge superstructures, the traffic load and/or lateral loads.
e) Landslide: Landslides occur when the slope changes from a stable to an unstable condition. This change in stability in slope, when hits the bridge, may lead to severe damage or even collapse of the bridge.

1.2 Manmade factors

Design and construction error leads to collapse of bridges. Most common defects include insufficient concrete cover, substandard concrete quality, in sufficient standards in reinforcement design, lack of detailing, inefficient bearings and expansion joint, inadequate waterproofing and drainage system, lack of seismic design parameters etc.

a) Overloading of bridges due to under estimation of vehicular traffic load may cause bridge collapse.
b) Collision due to vehicle impact causes serious damages to bridges.
c) Lack of inspection and maintenance leads to deterioration of bridge. A good maintenance program including regular inspection and proper rehabilitation will slow down this process.
d) Fires on bridges are commonly caused by the collision of vehicles such as fuel tankers or freight trucks and multiple vehicle collisions. Fires can lead to a significant decrease in the load-carrying capacity of the structural members due to reduction in the strength and stiffness of materials, which

can further lead to partial or full collapse of bridges.

2 REVIEW OBJECTIVES

The main objectives of assessment of existing structures are the assurance of structural safety and serviceability along with the minimisation of costs.

a. To determine the reliability of existing structure to carry current and future loads and to fulfil its task for a given time period;
b. Identify recent research efforts on the available techniques and investigation of adaptability of its applications;
c. Define the common procedure for assessing the strength, evaluating the safe load carrying capacity and provide information about rating and posting of bridge;
d. Understanding the knowledge gaps for further research.

3 METHODOLOGY FOR BRIDGE CONDITION ASSESSMENT APPROACH

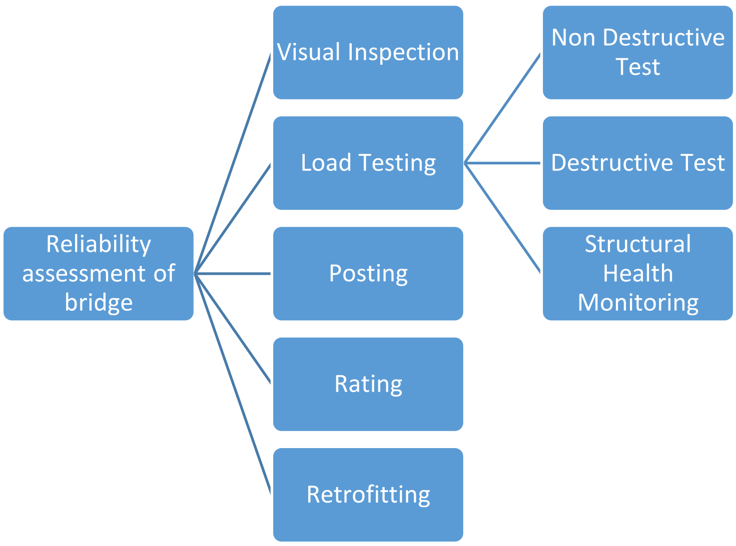

Figure 1. Methodology for bridge condition assessment

The main task of assessment is to ensure that the structure or parts of the structure do not fail under loading. The assessment is carried out for ultimate limit states, which are [1]:

- Limit state of equilibrium which means that bridge and its component act as rigid body and remains stable under ultimate load combination;
- Attainment of the maximum resistance capacity;

- Transformation of the structure or part of it into a mechanism, rupture, crushing or buckling.

A reduction of serviceability may lead to a limitation of use and therefore serviceability assessment might become necessary which includes [1]:
Excessive local damage due to cracking and spalling of concrete which may reduce the life span of the structure;
Excessive deflection or displacement causing discomfort to the users;
Excessive vibrations under dynamic effect of wind load causing fear to the users.

3.1 Visual inspection

The main aim of visual inspection is to establish a common procedure for assessing the strength, evaluating the safe load carrying capacity and provide information about rating and posting of bridge to owners, the traffic control authorities and users and the army officers in-charge of movement of military vehicles.

Visual inspection is the primary component of bridge management process. It is utmost important that bridge structure is under periodic or routine inspection followed by detailed technical examination. Hence Visual Inspection can be broadly done under two categories - detailed inspection and Routine Inspection. [3].

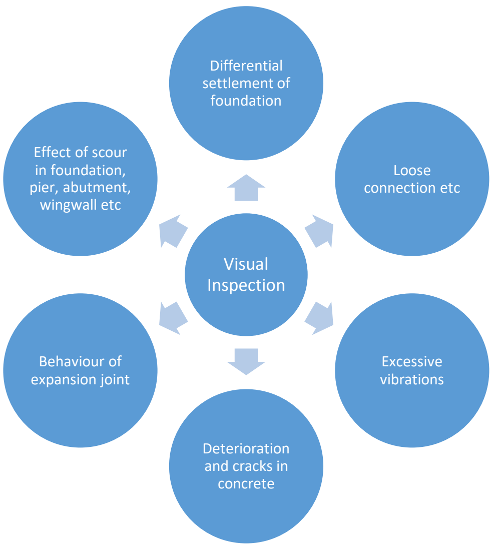

Figure 2. Methodology for visual inspection

For old bridges which had not been thus maintained from the beginning shall be inspected in detail and condition survey and investigation shall be carried out.

This may lead to minor repair work or major repair/rehabilitation. Rating and posting activities shall take cognizance of the extent of repair work or major repair/rehabilitation.

The following documents/data are to be procured to the extent available:

a) IRC Code, Specifications as applicable
b) Contract drawings updated to reflect as built details
c) Design calculations
d) Site records of construction
e) Soil investigation data before and during construction
f) Material test and load test data
g) Contract specifications
h) Post-construction inspection and maintenance reports
i) Details of all repairs/strengthening work carried out till the date of investigations
j) Hydrological, seismic and environmental data including changes if any (revision of zone for seismic classification and retro-fitting requirements as needed, and seismic retrofitting details, if carried out
k) Prevalent commercial vehicular loads plying on the bridge
l) Other natural hazards identified, if any.
m) Traffic survey data.

Structural condition Assessment of structural condition of bridge will take account of the following information which has to be collected during the detailed field investigation:

a) Cracking, spalling, honeycombing, leaching, loss of material or lamination of concrete members in superstructure, sub-structure and foundations.
b) Corrosion of rebars, exposure of rebars, corrosion in prestressing cables and structural steel members
c) In-situ strength of materials
d) Effectiveness and condition of structural joints viz. bolted, riveted and welded connections for steel bridges
e) Conditions of expansion joints, bearings and articulations hinges
f) Settlement, deformation or rotation producing redistribution of stress or instability of the structure.
g) Any possible movements of piers, abutments, skew backs, retaining walls, anchorages and any settlement of protective works and foundations
h) Hydraulic data covering scour, HFL, afflux, erosion at abutments variation, if any, in ground water table and discharging arising out of new irrigation projects or any other reason.

The detailed inspection is done by experienced bridge design engineers to assess the differential settlement of foundation, effect of scour in foundation, pier, abutment, wingwall etc., behaviour of expansion joint, deterioration and cracks in concrete, excessive vibrations, loose connection etc. [5] The routine inspection is generally applicable to short span bridges. It is generally conducted prior to monsoon and pot monsoon. The data collected prior to monsoon is compared to data collected post monsoon to assess the deterioration if any. Now a days innovative software has been developed which are helpful in interpreting structural health monitoring data. Such software typically consists of collective information to retrieve customized inspection guidelines and relevant historic bridge inspection data, capture bridge evaluation data, and automatically associate the captured information with the bridge components, making the bridge inspection documentation instinctive.

3.2 Load testing

Condition assessments for the existing concrete bridges are commonly addressed through structural analysis, load testing or a combination of methods. Load testing is a procedure to determine the safe load carrying capacity of a bridge, which in turn leads to posting and rating of bridge. Through static and dynamic load testing, the maximum deflection can be detected using strain gauges placed at critical locations on the bridge. Forced vibration techniques used excitations to determine the dynamic characteristics of bridge. [5] Load tests are broadly divided into two categories: non-destructive tests, which are intended as self-supporting alternatives to theoretical assessments, and destructive tests, which are intended to be used as an adjunct to theoretical calculations [6]. A combination of various tests may be required to assess the strength of structure.[1]

3.2.1 Non destructive tests

Such techniques are very commonly used for the concrete bridge deck assessment when the deterioration of structural member has already started. [8] Rebound and penetration test that measure the hardness of concrete are used to predict the strength of concrete. The hammer is used to compare the quality of concrete in different parts of the bridge rather than to determining the absolute values of strength. The relative strength of concrete can also be assessed by the Windsor probe[9]Sonic methods have been used for assessing the strength of concrete, the travel time of the sonic pulse between monitoring points is related to the modulus of elasticity and hence the strength, the system is capable of detecting differences between areas of sound and unsound concrete. Ultrasonic techniques are used for measuring the velocity of pulse in concrete. The pulse velocity depends on the composition and maturity of concrete and its elastic properties. The correlation between the pulse velocity and compressive strength is reasonably good provided the system has been calibrated with cores of particular concrete being evaluated. Corrections are required to be made to account for any reinforcement present. [10] Magnetic methods are used for determining the position of reinforcement as well as the assessment of concrete cover. Electrical methods used for inspection of concrete bridge components include resistance and potential measurements. These methods are particularly useful to detect corrosion of reinforcement [11].

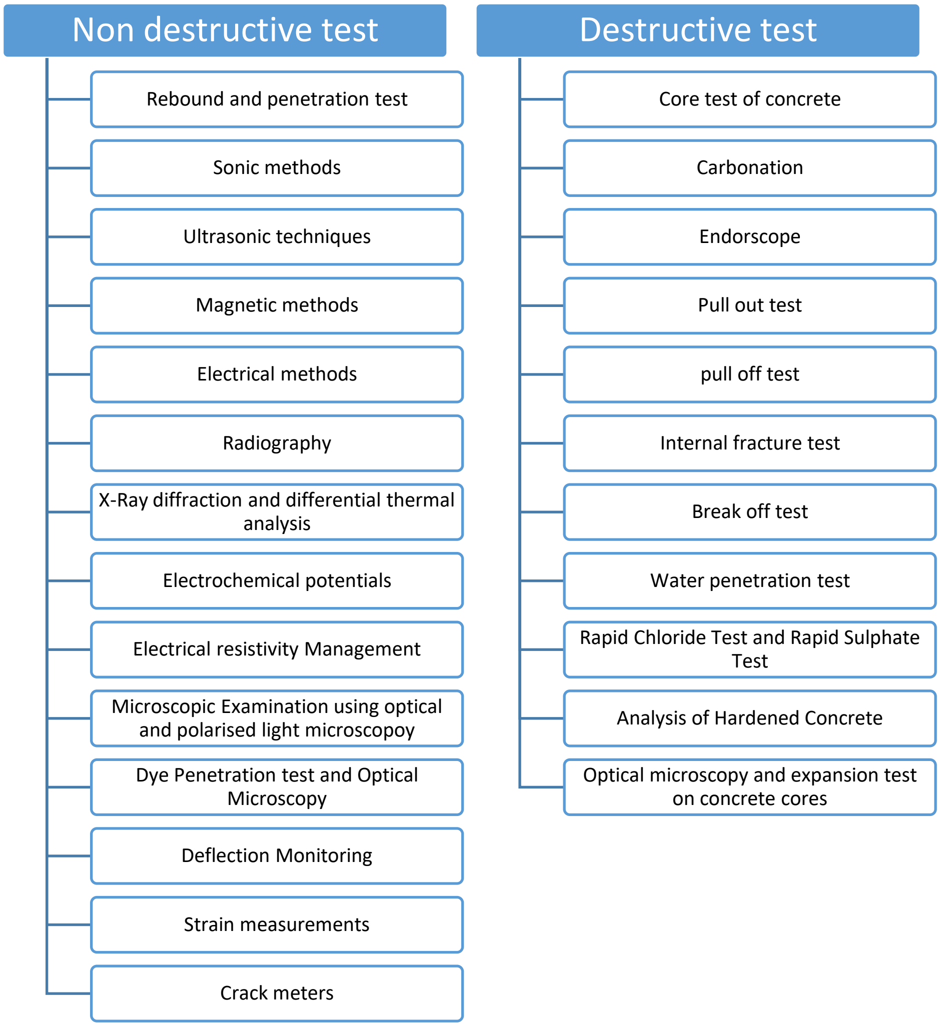

Figure 3. List of destructive and non destructive test

Radiography (gamma radiation techniques) have been particularly useful for assessment of voids in concrete as well as in grouted tendon duct. X-Ray diffraction and differential thermal analysis of concrete samples is useful in determining hydration characteristics the results indicate extent of attack due to sulphates or sea water and any unusual hydration product. Electrochemical potentials are useful in finding the condition of embedded steel [11]. Electrical resistivity Management is useful in indicating the condition of embedded steel. [11] Microscopic Examination using optical and polarised light microscopy is useful in identifying aggregate source, presence of slag etc. Dye Penetration test and Optical Microscopy give qualitative evaluation of incidence of pores and voids in concrete. Deflection Monitoring is done with precision levels, theodolites, laser aligners. Strain Measurements are done with the help of strain gauges and strain measuring devices. Crack meters are used to measure the width of cracks.

3.2.2 Destructive tests

Concrete strength is obtained by testing of core samples from concrete components under reference results in the actual strength of concrete being obtained. Core drilling equipment is available in various formats for taking cores in horizontal, vertical or inclined directions. Battery powered portable versions are also available.

Carbonation of concrete in the cover region results in loss of protection of the steel against corrosion. The depth of carbonation is measured by painting the freshly coated concrete surfaces with the 2 percent solution of phenolphthalein. The colour of the concrete surface after painting may be compared with standard charts to indicate the areas of carbonation. Endorscope consists of usually flexible viewing tubes that can be inserted into holes drilled into the concrete bridge components. A light is provided by optic fibres from an external source. Endorscopes are used for detailed examination of parts of the bridge structure which could not otherwise be assessed. Endorscopes are also available with attachments for a camera or TV monitor. Pull Out Test measures the force required to pull out a steel rod with enlarged head cost in concrete or introduced by drilling. It is impossible to estimate compressive and tensile strength of concrete by correlating with the pull-out force. Pull Off Test is used to evaluate the tensile strength of concrete or the bond tensile strength between two different concrete or mortar layers. The tensile force is applied to a circular steel disc 50 mm diameter glued to a concrete surface by an epoxy resin. The test can be carried out with a portable light weight equipment. The steel disc diameter is 50 mm and the pull off force ranges from 500 N to 50000 N depending on the type of equipment. This test is easy to operate at site and can be used specially for the quality control of repaired concrete surfaces. Internal Fracture Test - In this the force required to pull out an anchor bolt is measured. It is used to estimate tensile strength of concrete through a correlation with the pull-out force. Break Off Test - this is mainly used to estimate flexure tensile strength of concrete. 55 mm diameter core, 70 mm deep is prepared and the force required at the top right angles to the axis to break off the core at the bottom is measured. The core is drilled in the hardened concrete. The test can also be used to evaluate bond between two concrete or mortars of different ages.

Water Penetration Test measures the flow rate of water through concrete and this indicates the degree of protection of reinforcement offered by the concrete cover. The specimen is sealed in a permeability test ring and water pressure applied on one face and the flow rate is measured. The test is susceptible to laboratory conditions of storage. Rapid Chloride Test and Rapid Sulphate Test results in terms of chloride content and also depth wise penetration are possible. Analysis of Hardened Concrete can determine the cement content in hardened concrete. Optical microscopy and expansion test on concrete cores can detect the alkali-aggregate reaction.

3.2.3 Structural health monitoring

SHM is about assessing the in-service performance and integrity of bridges on a continuous real time basis using variety of measurement techniques. It deals with data collection and precise measurement of structural element condition, implementation of damage detection and characterization of strategy so as to ensure safety of the structure as a whole. SHM techniques uses the change in measurement at the same location at two different times to identify the structural condition of bridges elements. SHM involves collection, interpretation and analysis of data in order to quantify the severity of existing damage and predict the future life of structure. Static based SHM involves measurement of altered displacement, rotation etc. Dynamic based SHM involves measurement of altered structural response, frequencies, mode shapes, damping or modal strain energy change etc. By measuring the structural response by means of sensors strategically placed on the structure, and intelligently analysing these measured responses, it is possible to identify damage occurrence.[15] The latest advances on sensor technology for structural health monitoring has resulted in various types of SHM sensors. Now a days wide variety of SHM sensors are used for structural monitoring. Fibre Optic Sensors can be used to measure different parameters such as strains (both static and dynamic), structural displacements, vibrations frequencies, acceleration, pressure, temperature, and defects like delamination, cracks, corrosion, concentration of chloride ions etc. FOS are generally surface mounted on existing structures, or embedded in newly constructed structures. The obtained data can be used to evaluate the safety of both new-built structures and repaired structures. They have been proved useful in strain monitoring of concrete components of bridge. [16]

Accelerometer is an electromechanical device used for measuring acceleration forces through single or multi-axis directions. They can detect both the magnitude and the direction of the proper acceleration, as a vector quantity. Such forces can be static, like the continuous force of gravity on structural components, or dynamic to sense motions or vibrations like when a truck crossing a bridge. [16] Piezoelectric accelerometer is an accelerometer that employs the piezoelectric effect of certain materials (e.g. quartz) to generate electric charge in response to applied mechanical stress. This type of vibration transducers offers a very wide frequency and dynamic range. Vibrating wire Transducers are very popular for geotechnical and structural monitoring purposes. The principal component of the vibrating wire sensor is a tensioned steel wire that vibrates, when pulled, at a resonant frequency that is proportional to the strain in the wire. This mechanism is used to measure static strain, stress, pressure, tilt, and displacement through various sensor configurations. Vibrating wire strain gauges are widely used to measure strain in steel or in reinforced concrete and also crack width measurement in bridges.

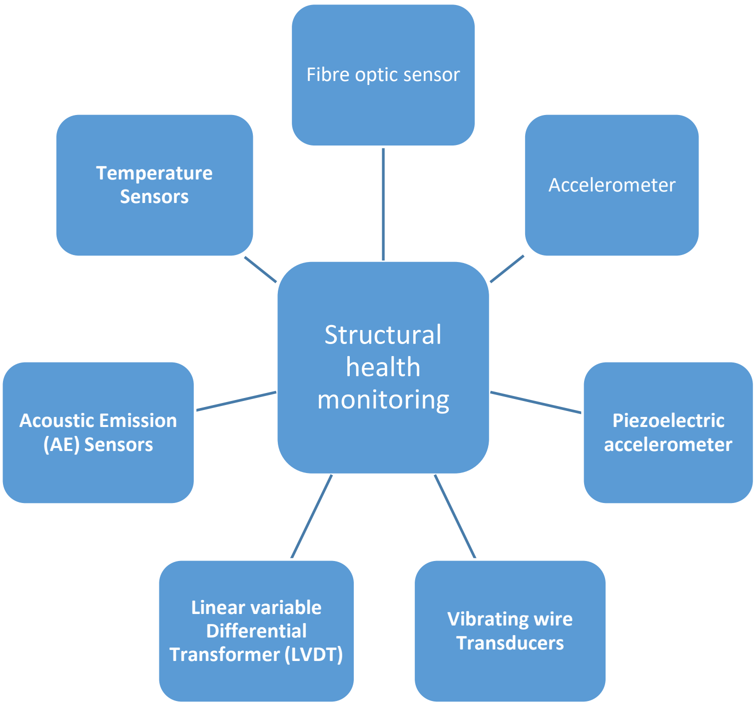

Figure 4. Techniques for structural health monitoring

Linear variable Differential Transformer (LVDT) is an electromechanical sensor used for measuring linear displacement. and are frequently used in recording displacement on structural members due to live loads and temperature variations. Acoustic Emission (AE) Sensors measure high-frequency energy signals that are generated from local sources of stress waves. Discontinuities and defects in a material generate stress waves. AE sensors are able to pick up the stress waves propagated to the material’s surface. By converting these waves into electrical signals, AE sensors are ideal devices to effectively assess the current state of materials under stress. These sensors are mainly used to detect the onset or growth of existing cracks in structural components. Temperature Sensors are useful to measure the temperature that affects physical properties of structures to some extend in civil engineering structures that are subject to the environmental changes. Thermocouples are one of the most widely used temperature sensors to measure the variations of temperature in certain points of the structure. Most of the large concrete structures use temperature sensors, while casting and during construction, in order to have a full control over temperature changes under curing. [20]

3.3 Posting of bridges

It implies the restriction on the use of bridge in order to sustain its safe load carrying capacity. This can be achieved by either load limit postings or speed limit postings.[3] Load limit posting allows the load restriction on bridge in the form of maximum axle load or maximum gross load of vehicle. Advance warning signs on load carrying capacity of bridge are placed well ahead of bridge about 200 m from abutments on either side. Load restriction signs, mentioning the load limit, are placed well in advance about 60 m before approaching the abutment on either side. Speed posting allows the restriction on speed so as to reduce the stresses developed due to fast moving heavy moving vehicles on bridges. This will reduce the impact on bridge so that it can carry heavy loads with reduced vehicle speed. Depending upon the assessment of the bridge condition. The rating/posting engineer would decide the necessity of the following traffic restrictions on the bridge from safety considerations till the exercise of posting is completed. i) Speed Restriction - to be effective till the detailed investigations and strengthening or rehabilitation work and load testing (if required) on the repaired bridge is complete. The limiting speed of vehicles over the structure will be decided by the bridge authority depending upon the physical condition of the structure.

Generally, speed restrictions are not favourable and restricted to exceptional cases only. ii) Geometrical Restriction -this would involve curtailing the carriageway width to ensure lesser extent of live load on the bridge at a particular time and/or installation of height barrier on either end approaches to restrict passage of overloaded or oversized commercial vehicle on the bridge. iii) Footpath Loading - depending upon the structural condition of the footpath slab, restriction on load on footpath may be imposed till the distressed part is rehabilitated. Restriction on footpath load may also be; necessary in order to reduce the total load on the bridge superstructure.

3.4 Rating of bridges

It is a process of assessing safe load bearing capacity of existing old bridges which are not designed as per the current prevalent codal provision. Rating of old bridges for which original designs are not available, and the re-evaluation of previously rated structures in situations where bridge had suffered deterioration of strength of any of the main components from superstructure to foundations, requires careful and detailed evaluation of many complex factors and conditions. The main purpose of rating is to suggest various measures to ensure safety of bridge throughout its remaining life span. And also, to avoid dismantling existing bridges and reconstruction of bridge which in turn results in saving of time and money. Field data is collected through site inspection and investigations by trained engineers who recognise, register and evaluate the structural condition of bridge element. Nowadays smart computers and modern non-destructive equipment are used for condition assessment of existing bridges. The findings are correctly interpreted and suitable measures are suggested to remove the structural deficiency of bridge.[23] Load Test for rating is also done when it is not possible to determine the rated capacity of a bridge due to lack of essential details as per new revised codes.

3.5 Retrofitting of bridges

If the bridge has become structurally over stressed due to hazards like floods, earthquakes etc various retrofit applications have been developed, for improving the strength and ductility of bridges or bridge components. Also bridges located in seismic prone areas, are not capable of withstanding earthquake forces due to lack of compliance to current codal provision. The seismic performance of existing bridges requires re–evaluation as design of such bridges are deficient of earthquake forces. Moreover the increase in live load intensity, increase in tractive and braking forces etc as per revised codes does not reflect in old bridges. Hence need for retrofitting of existing bridges arises as the seismic behaviour of such bridges is generally affected by their original structural inadequacies, material degradation due to aging and alterations carried out during use over time. Retrofitting can be done statically by strengthening the bridge structural members and seismically to meet the current code requirement. Static retrofit methods include: dead load reduction, increase of flexure and shear capacity, installation of post tensioning systems, FRP strengthening, substitution of bearings, elimination of deck joints. Seismic retrofit methods include: strengthening of piers, provision of additional confinement reinforcement, use of damping device, use of FRP.

4 CONCLUSION

Structural safety and condition assessment of bridge is a scientific method aimed at assessment of bridge health and its structural integrity to prolong its life span. The whole process of interpretation of bridge condition assessment is very complex due to visual inspection. It is effective in identifying flexure and shear crack, scaling and spalling of concrete but it has got limitations in assessing hidden defects such as sub surface delamination, rebar corrosion etc. Load testing is an effective means of understanding the structural response of a bridge without causing any damage, but it is costly and time consuming. SHM practises ensures that functionality of bridge is assessed with higher accuracy to avoid any disastrous failure. It ensures increased public safety and enhances the service life of bridge. The main limitation is that the techniques adopted need to be monitored on continuous basis. Moreover, wireless sensors are battery operated which may cause error due to environment related problems. Non-destructive test is economical, precise and accurate but its scope is limited if only one technology is used and it requires trained personnel for data collection and analysis. [24] The commonly used condition rating systems are approximate, subjective in their evaluation, and are generally inadequate as a measure of bridge performance since they still largely depend on visual inspection. Despite the fact that NDE and SHM systems have become the most effective and significant methods for bridge condition assessment, still there are a limited number of studies that addresses uncertainty in accuracy and reliability of their measurement techniques.

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