DESIGN OF RESTRAINERS FOR AN RC BRIDGE: A CASE STUDY

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Abstract: Damage to bridges due to earthquakes has become quite common, which has developed a new interest among engineers and researchers. Retrofitting of old bridges and seismic design of new bridges has been the most challenging work. Since the development of modern codes, it has become easier and much better. Before the bridges were designed for nominal seismic force without provision of ductility. This lead to much more failure of bridges during an earthquake. Bridges have been useful in all kinds of disaster and disruption hampers relief and rescue operation. Therefore, it becomes necessary that all bridges are able to resist all kinds of disaster that can lead to failure. For this case, several retrofitting techniques have been developed so that an existing structure is able to resist any kind of disaster. In this research, restrainers have been designed for a three-span RC bridge so that there is limited relative displacement and can withstand any kind of seismic activity.

Index terms- **retrofitting, nominal seismic force, ductility, seismic activity.**

I. INTRODUCTION.

Bridges have been a part of our system much before the introduction of seismic codes. However, during those times, bridges were designed without any consideration for the seismic activity. This made them vulnerable during an earthquake. In today’s world various seismic codes are available, thus all the structures are constructed with due consideration to the seismic codes. Also, in order to prevent any damage or eliminate any danger to life, bridges that have constructed much before there was any provision for seismic codes, need retrofitting. For any structure, the technique of modifying the structure such that it is able to resist any seismic activity is called retrofitting.

Bridges that have been constructed before and those which are at risk of failure, have been analysed time after time. It has been seen that the bridge piers due to lack of transverse steel and confinement have the inadequate shear capacity with premature termination of steel. Some of the ancient bridges lacked restraining devices and bearings, which made them vulnerable to failure. It has been found that most of India's bridges are structurally deficient or functionally obsolete, which makes them not only unsafe but vulnerable to earthquakes.

Retrofitting of any structures is done in order to make it seismically stable. A bridge needs retrofitting in either of the two scenarios, which are (i) any existing bridge that has not experienced any damage, but is unable to meet the requirements of current codes, thus being vulnerable during an earthquake, (ii) the bridge has been damaged and needs to undergo repair and retrofitting.

II. METHODOLOGY.

Retrofitting means to make any structure seismically resistant i.e. prone to damage during an earthquake. Instead of replacing any structure, which is not seismically fit, a better solution is to retrofit. In the past several years, this technique has received notable attention i.e. more and more retrofitting programs have been taken up. Many retrofitting techniques are there to improve the resistance of bridges towards seismic activity. However firstly, certain issues are to be considered before going for retrofitting of a bridge viz., evaluation of seismic capacity of a bridge, identifying deficiencies, ageing effects, decision on level of retrofitting, hazard level for design, performance criteria, developing alternate strategies of retrofitting, choice of right strategy, re-evaluation of retrofitted structure, validating effective retrofitting measures and health monitoring of retrofit bridges (Thakkar,2008).

2.1 Damage in bridges

In order to know what retrofitting would be suitable to use, it is very important to know about the bridge damage and the causes and location of damage. Certain common damages that have been seen in the past and are most likely to occur are (i) damage to the bridge span, which included falling of the bridge span from the supports or development of crack in the deck slab (ii) failure of the bearing (iii) failure of the expansion joint (iv) Damage to the piers or substructure damage (v) liquefaction failure (Thakkar,2008)..

2.2 Structural deficiencies.

The performance of bridges in the past earthquakes has led to the conclusion about the various structural deficiencies. In the superstructure, the spans can get dislodged from the supports if there is no linkage between two spans. Bearing failure can occur when these are unable to withstand forces generated from the superstructure. Inadequate seat length can also result in unseating of the span. In the substructure, lack of flexural strength, shear strength, insufficient transverse reinforcement, less ductility can be the certain factors responsible for the failure. The inadequacy of foundation and soil strength can lead to unequal settlements thus leading to substructure failure (Thakkar,2008).

2.3 Retrofitting techniques.

There are five primary retrofit measures used to retrofit bridges viz. seismic isolation, seat extenders, restrainers, bent cap strengthening and column strengthening. These methods can be either applied individually or in combination with the objective of reducing overall vulnerability to seismic loading (Thakkar,2008).

2.3.1 Restrainers.

Longitudinal bar and cable restrainers are used to prevent excessive longitudinal movement of bridge spans. Steel bars or cables attached to adjacent spans or to the bridge abutment to limit the longitudinal displacement of the bridge deck. Cable restrainers have been used extensively in California and have been identified as a relatively simple and inexpensive retrofit strategy to minimize the risk of unseating (Priestly, et.al. 1996). To prevent unseating in simply supported bridges during strong earthquakes, American Association of State Highway and Transportation Officials (AASHTO) and the California Department of Transportation (Caltrans) have recommended the restrainer design methods (Saiidi. et. al, 2001).

A comparison between cable and bar showed that the elastic stiffness of one bar was equal to twelve cables but the elastic range of cables is much more than bars (Anon., 2008). Unseating of intermediate (in-span) hinges calls for the need of using an adequate number of restrainers to limit the relative displacement (Desroches et. al, 2000)

Restrainer cables usually consist of galvanized 0.75 in. (19mm) diameter steel cables and have lengths between 5 ft (1.52 m) and 10 ft (3.05 m). Depending on the ambient temperature conditions in the region of installation, the slack provided may be up to 0.75 in. (19 mm). High-strength galvanized ASTM-A 722 bars are similar to restrainer cables, except have more stiffness than cables. The motive of the restrainer design is that the restraining component should remain in the elastic region, so the added ductility of bars is not considered a major advantage. The reduced flexibility also implies that the bars are much longer than cables in order to allow for the same range of motion of the structure. For these two reasons, restrainer bars have historically been used much less frequently than restrainer cables (FHWA,2006)

2.4 Design of Restrainers

For the particular RC bridge, we design the restrainer cables which are to be used for retrofitting. The design given below for restrainers is for a three-span RC bridge with span 12.4m, 12.5m, and 12.620m respectively. The bents consist of three columns each with a diameter of 1m. The damping ratio is 5 %. The restrainer cables are designed for hard soil for PGA of 0.24g.

Diameter of columns= 1m
Height of column=8m
Number of columns on each frame=3
Weight of frames=19.56 MN
Column bent stiffness= 304.85 KN/mm
Hinge seat width=152mm
Damping ratio=5%
Slack length= 19mm, usually taken between 0-19mm
Displacement ductility, µ=5 (since there are 3 columns on each bent)

1. Maximum hinge displacement
   $D_y = D_r - D_s$
   D_y = Restrainer Elongation at yield.
   D_r = Allowable hinge displacement.
   = Hinge seat width – Minimum required
   Assume minimum required width is 32 mm
   $D_r = 152 - 32 = 120\ mm.$
   D_s = Restrainer Slack = 19 mm.
   $D_y = 120 - 19 = 101\ mm.$
   Length of Restrainer, L = $\frac{D_y E}{F_y}$
   Where, F_y = Standard yield stress for cables = 1.21 x 10³ KN/mm².
   E= Modulus of Elasticity = 6.89 x 10^4 KN/mm²
   $L = \frac{101x\ 6.89\ x10^4}{1.21x\ 10^3}$ =5751 mm =5 m
2. Initial hinge displacement
   K_{eff_1} = Effective stiffness of individual frames $= \frac{304.85}{5} = 60.97\frac{\text{KN}}{\text{mm}}$
   $K_{eff_2} = \frac{304.85}{5} = 60.97\frac{\text{KN}}{\text{mm}}$
   T_{eff_1} = Effective time period for first frame $= 2\pi\sqrt{W/(g\ x\ K_{eff_1})}$ = 1.13 s
   T_{eff_2} = Effective time period for second frame $= 2\pi\sqrt{W/(g\ x\ K_{eff_2})}$ = 1.13 s

ξ_{eff} = Effective damping = $\xi + \dfrac{1-\frac{0.95}{\sqrt{\mu}}-0.05\sqrt{\mu}}{\pi} = 0.19$

ρ_{12} = Cross- correlational coefficients

$$= \frac{8\,(\xi_{eff})^2\,(1-\beta)\beta^{3/2}}{(1-\beta^2)^2+4\left(\xi_{eff}\right)^2(\beta)(1+\beta)^2}$$

β = Ratio of modal frequencies

$$= \left(\frac{\xi_{eff}}{\xi}\right)^{0.3} = 1.5$$

$\rho_{12} = 0.54$

Individual frame displacement, D_{10}, D_{20}

$$D_{10} = \left(\frac{T_{eff_1}}{2\pi}\right)^2 S_{a1}\left(T_{eff_1}, \xi_{eff_1}\right),\ D_{20} = \left(\frac{T_{eff_2}}{2\pi}\right)^2 S_{a2}\left(T_{eff_2}, \xi_{eff_2}\right)$$

$S_a\left(T_{eff_1}, \xi_{eff_1}\right)$ = pseudo acceleration response ordinate for T_{eff} & ξ_{eff}

S_{a1} = 0.61g, S_{a2} =0.61g

$D_{10} = \left(\frac{1.13}{2\pi}\right)^2$ x 0.61 x 9810 = 193 mm

$D_{20} = 193$ mm.

D_{eq_0}= Hinge displacement

$$= \sqrt{{D_{10}}^2 + {D_{20}}^2 - 2\rho_{12}D_{10}D_{20}}$$

= 185 mm

⇨ $D_{eq_0} > D_r$

Therefore, restrainers are required.

3. Initial restrainer stiffness, K_{r1}

$K_{m_{eff}}$ = Effective stiffness = $\dfrac{K_{eff_1}K_{eff_2}}{K_{eff_1}+K_{eff_2}}$ = 30.485 KN/mm

$K_{r1} = \dfrac{K_{m_{eff}}(D_{eq_0}-D_r)}{D_{eq_0}}$ = 10.709 KN/mm

4. Hinge displacement, D_i

$D_i = P_i S_{a_i}(T_i, \xi_i)$

P_i = participation factors

$$= \frac{\phi_i^T M\, I}{\phi_i^T K\, \phi_i}\ (a^T, \phi_i)$$

$a^T = [-1, 1]$

ϕ_i = Mode shapes = $\begin{Bmatrix}\phi_1\\ \phi_2\end{Bmatrix}$

The vibration frequencies and mode shapes are the solutions of the eigenvalue problem:

$K\phi_i = \omega_{eff_i}^2 M\phi_i$

Where K = $\begin{bmatrix}K_1+K_r & -K_r\\ -K_r & K_2+K_r\end{bmatrix}$

M = $\begin{bmatrix}m_1 & 0\\ 0 & m_2\end{bmatrix}$

$\omega_{eff_i}^2 = \begin{Bmatrix}\omega_{eff_1}^2\\ \omega_{eff_2}^2\end{Bmatrix}$

Therefore we have:

$$\begin{bmatrix}K_1+K_r & -K_r\\ -K_r & K_2+K_r\end{bmatrix} = \begin{Bmatrix}\omega_{eff_1}^2\\ \omega_{eff_2}^2\end{Bmatrix}\begin{bmatrix}m_1 & 0\\ 0 & m_2\end{bmatrix}$$

$$\begin{bmatrix}71.67 & -10.7\\ -10.7 & 71.67\end{bmatrix} = \begin{Bmatrix}\omega_{eff_1}^2\\ \omega_{eff_2}^2\end{Bmatrix}\begin{bmatrix}1.99 & 0\\ 0 & 1.99\end{bmatrix}$$

⇨ $\begin{Bmatrix}\omega_{eff_1}^2\\ \omega_{eff_2}^2\end{Bmatrix} = \begin{Bmatrix}30.6\\ 30.6\end{Bmatrix}$

$T_{eff_1} = 2\pi/\sqrt{30.6}$ =1.13 s

$T_{eff_2} = 2\pi/\sqrt{30.6}$ =1.13 s

Calculating ϕ_i :

We know [K – $\omega_{eff_i}^2$ M] ϕ_i = 0

$$\left[\begin{bmatrix}71.67 & -10.7\\ -10.7 & 71.67\end{bmatrix} - \begin{Bmatrix}30.6\\ 30.6\end{Bmatrix}\begin{bmatrix}1.99 & 0\\ 0 & 1.99\end{bmatrix}\right]\begin{Bmatrix}\phi_1\\ \phi_2\end{Bmatrix} = 0$$

On solving, we get:

$\{\phi_1\} = \begin{Bmatrix} \phi_{11} \\ \phi_{12} \end{Bmatrix} = \begin{Bmatrix} 0.19 \\ 1 \end{Bmatrix}$, $\{\phi_2\} \begin{Bmatrix} \phi_{12} \\ \phi_{22} \end{Bmatrix} = \begin{Bmatrix} 1 \\ 0.19 \end{Bmatrix}$

Participation Factors:

$P_1 = \frac{\phi_i^T M\, I}{\phi_1^T K\, \phi_1}\ (a^T, \phi_1)$ =0.006 s^{-1}

$P_1 = \frac{\phi_2^T M\, I}{\phi_2^T K\, \phi_2}\ (a^T, \phi_2)$ =0.006 s^{-1}

Calculating hinge displacement using Response Spectrum

$S_{a1} = 2158\, mn/s^2$

$S_{a2} = 2158\, mn/s^2$

$D_1 = P_1 S_{a1} = 13\, mm$

$D_2 = P_2 S_{a2} = 13\, mm$

$\beta = \left(T_{eff_2} / T_{eff_1}\right)^{0.3} = 1$

$\rho_{12} = 1$

=> D_{eq_0} = Hinge displacement

$= \sqrt{D_{10}{}^2 + D_{20}{}^2 - 2\rho_{12} D_{10} D_{20}} = 0$

$D_{eq_0} < D_r$

Therefore, restrainers are not needed to prevent hinge displacement. However, the minimum number of restrainers will be provided.

5. No. of restrainers, $N_r = K_{rj} D_r / F_y A_r$

Where $A_r = 143\, mm^2$

$N_r = 7.42 = 8$

Therefore, we provide 8 restrainer cables. The restrainer units have 5 cables for each unit. We provide two units i.e. 10 cables.

Minimum restrainer stiffness

K_r= 0.50 K_{meff}

= 15.24 KN/mm

$N_r = 10.57 = 10$ Restrainer cables (Saiidi. et. al, 2001).

III. RESULT AND DISCUSSION

A restrainer to be used as a retrofit measure can be a bar or a cable. Restrainers are designed in such a way that they are not used to dissipate seismic energy (Anon., 2008). Restrainer cables used for retrofitting purpose are better than restrainer bars because of their flexibility. In order to resist any kind of displacement, the ductile nature of the retrofit measure is important. In restrainer bars, there is less ductility which makes them prone to sudden failure while as in cables the chances of sudden failure are less.

The restrainer cables to be used for the RC bridge would be provided in two units. Each unit will have five cables. The stiffness of each cable is 15.24 KN/mm. Therefore, ten cables will be provided, so that the displacement of the structure is less and it is less vulnerable during any seismic activity.

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