Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 73/1/73/2 (1995)

Artikel: Preventive measures for reducing the seismic risk of bridges
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DOI: https://doi.org/10.5169/seals-55386

Preventive Measures for Reducing the Seismic Risk of Bridges

Mesures pour la réduction du risque sismique des ponts

Massnahmen für die Reduzierung des Erdbebenrisikos von Brückenbauten

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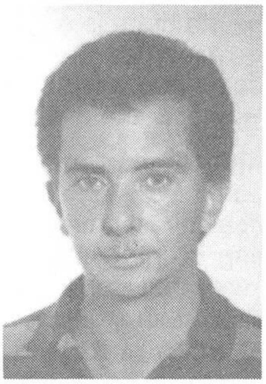

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SUMMARY

With specific reference to the seismic reliability of existing bridges and highway networks, the design of preventive upgrading interventions is discussed. Results are presented of a numerical analysis of the seismic response of multispan bridges, aimed at evaluating the efficiency of different upgrading techniques. A procedure is illustrated for assigning priorities among the bridges included in a highway network, allocating the available resources in an optimal way. Three possible objective functions are considered, namely the reliability of the network, the time-effciency of the interventions and the out-of-service time of the network in case of a severe earthquake.

RÉSUMÉ

Les problèmes d'intervention en vue du renforcement sismique des ponts sont présentés. Les résultats d'une analyse numérique concernent la réponse sismique des ponts avec tablier en béton armé; elles permettent d'évaluer la validité de différentes techniques de renforcement. La définition des priorités d'intervention sur les ponts situés dans un réseau autoroutier permet d'optimaliser les ressources disponibles. Trois objectifs sont fixés: la fiabilité du réseau, l'efficacité temporelle des interventions et la durée hors de service du réseau en cas de séisme.

ZUSAMMENFASSUNG

Es wird die Planung von Verbesserungsmassnahmen präsentiert, die besonders den Fall der seismischen Zuverlässigkeit von existierenden Brücken bzw. des Autobahnnetzes betreffen. Als erstes werden die Ergebnisse einer ausführlichen numerischen Analyse der seismischen Antwort von Stahlbetondurchlaufträger (Brückenträger) dargestellt. Eine Prozedur wird dann eingeführt, die die Prioritäten innerhalb der im Netz befindlichen Brücken zuordnet; hierzu werden die verfügbaren Ressourcen so zugewiesen, dass einige Funktionen maximiert werden. Folgende drei Funktionen werden in Betracht gezogen: die Zuverlässigkeit des Netzes zu garantieren, die zeitliche Effizienz der Eingriffe, und die Dauer der Ausfallszeit des Netzes im Falle eines starken Erdbebens.

1. INTRODUCTION

Apart from conservation of architectural heritage, there are several motivations for extending the lifespan of a constructed facility: from economic convenience to the minimization of environmental impact (to restore a structure is usually less traumatic than to demolish and rebuild), to the need of maintaining continuously effective a lifeline or service network.

To tackle rationally the problem it is necessary to assess the present strength of the structure, the foreseeable evolution of its reliability and, if either are deemed unsatisfactory, the feasibility and costs of repair/upgrading interventions versus the availability of economic resources. In fact, the design of preventive interventions is (or at least should be) the result of a decisional process involving a cost-benefit analysis of the possible interventions on the considered structure: from this viewpoint, the decisions would be - in principle - immediate. However, account should also be taken of the fact that often the structure is an element of a system (in full rigour, this is always the case) and that the available resources are usually limited: therefore the interventions must be planned in function of their costs and effectiveness with regard to the reliability of each structure and of the system as a whole, that is, the available resources must be allocated in an optimal way.

Both aspects are dealt with in this short paper. In Section 2, the effectiveness of alternative upgrading interventions is studied with reference to typical reinforced concrete girder bridges, through an extensive numerical investigation on the consequent reduction of their fragility. Then, Section 3 tackles the planning of interventions on bridges considered as critical elements of a highway network, in such a way that, for a given amount of available resources, an appropriate objective function is maximized. More details on assumptions, procedures and results can be found in the References listed at the end of the paper.

2. SEISMIC UPGRADING OF R.C. GIRDER BRIDGES

The investigation summarized here is aimed at optimizing the choice and the design of the interventions for seismic upgrading of existing r.c. bridges: this information is missing from current codes, that do not supply neither general concepts nor special provisions for retrofitting.

A specific structural type is investigated [4][5]: namely, multispan r.c. girder bridges made by a simply-supported (s.s.) or continuous (cnt.) horizontal deck and vertical piers of different height and section.

The layouts of the case examples are shown in Table 1. It can be noted that almost all bridges are characterized by piers with strongly different stiffnesses: indeed, such bridges are very vulnerable to seismic action and also prone to degradation, due to the major demand for ductility in the critical sections of the stiffest piers (the 4th, 8th and 11th cases are introduced for comparison). Three cross sectional shapes of the piers are assumed: two hollow rectangular (A and B) [4] and one hollow circular (C) [5].

Two techniques for upgrading are examined: the first one (J) consists in jacketing the piers with a shotcrete cover and adding steel reinforcement (Table 2); the second (IS) modifies the structural response by replacing the existing girder bearings with isolation/dissipation (i/d) devices.

In the design of IS interventions, two main problems arise: (a) the optimal balance between the yielding forces of the devices and their deformability; (b) the choice of the most suitable location and orientation of the devices, and in particular whether these devices should be arranged on all piers or only on the stiffest piers. Several solutions are tried, as described in detail in [4][5].

Among the possible causes of failure, only structural damage is considered. It is assumed that the piers are the critical elements of the structural systems, and that the failure of only one pier determines the failure of the bridge. A damage and a collapse limit state condition are considered, respectively identified with the attainment of the values 0.4 and 1.0 of the damage indicator proposed by Ang (1987) [4]. If the bridges are retrofitted by the second technique, another constraint is introduced, that is, the maximum required displacement ductility in the i/d device is limited below a threshold value (10 in the specific case).

The seismic fragility (i.e., the probability of attaining a limit state vs. the intensity of the action) of the assumed existing and retrofitted bridges is obtained numerically by applying an improved MonteCarlo procedure; artificial accelerograms, consistent with the spectrum S2 of Eurocode N.8 and scaled to a peak ground acceleration a_g in the range 0.10-0.45 g, are assumed as inputs.

Bridge	*Deck*	*Span*		*Piers*	
		number	*length (m)*	*type*	*height (m)*
1	s.s.	4	50	A	10 - 30 - 20
2	s.s.	5	50	B	40 - 10 - 10 - 40
3	s.s.	5	50	A	10 - 20 - 20 - 10
4	s.s.	9	40	A	10 - 20 - ... - 20 - 10
5	s.s.	4	40	B	20 - 40 - 20
6	s.s.	4	50	C	10 - 30 - 20
7	s.s.	4	50	C	40 - 10 - 20
8	s.s.	4	50	C	20 - 20 - 20
9	cnt.	4	50	C	10 - 30 - 20
10	cnt.	4	50	C	40 - 10 - 20
11	cnt.	4	50	C	20 - 20 - 20

Table 1 *Layout of examined bridges*

Intervention type	*Pier section*	*Cover thickness (m)*	*Ratio between added and existing reinforcement (%)*
J1	A / B	0.08	50
J2	A / B	0.16	100
J3	C	0.10	50
J4	C	0.15	75

Table 2 *Characteristics of jacketing interventions*

Inspection of the fragility curves of the piers in their present conditions shows that damage and collapse probabilities are rather large, especially for the stiffest piers (10 m tall) and for $a_g > 0.25g$.

The effects of jacketing interventions of types J1-J4 are shown in Fig. 1, in which the ratio ξ between the probability of attaining the damage limit state and the corresponding value for the assumed existing piers is plotted in a semi-logarithmic scale. It can be noted that the effects of the J1 and J3 interventions are comparatively small: the mean value of ξ (ξ_{avg}) is equal to 0.6. ξ decreases with a_g and is practically equal to 1 if $a_g > 0.3g$. J2 intervention is slightly more effective ($\xi_{avg} = 0.3$). J4 intervention worsens the structural response, because it reduces excessively the curvature ductility of the pier section (therefore, J4 is not reported in Fig. 1). The effects of interventions J1-J2-J3 are larger for taller piers, whose influence on the structural safety is smaller. Similar results are obtained with regard to the collapse limit state: ξ_{avg} is equal respectively to 0.35 and 0.1 for interventions J1-J3 and for intervention J2.

Analogous results are also obtained when the failure of the bridge schemes of Table 1 are considered instead of failure of the individual piers.

It may be concluded that:

- strengthening the piers by concrete jacketing has a limited effect (the damage probability is reduced no more than by one or two orders of magnitude; the collapse probability remains practically unchanged if $a_g > 0.25g$);
- these interventions are convenient when the piers are highly ductile, and the expected seismic intensity is low;
- the expansion joint in the s.s. deck cannot be eliminated, since this intervention would involve an increase in the forces acting on the stiffest piers and in the ductility demand; indeed, the joint can be eliminated only in the case of bridges characterized by piers of the same height.

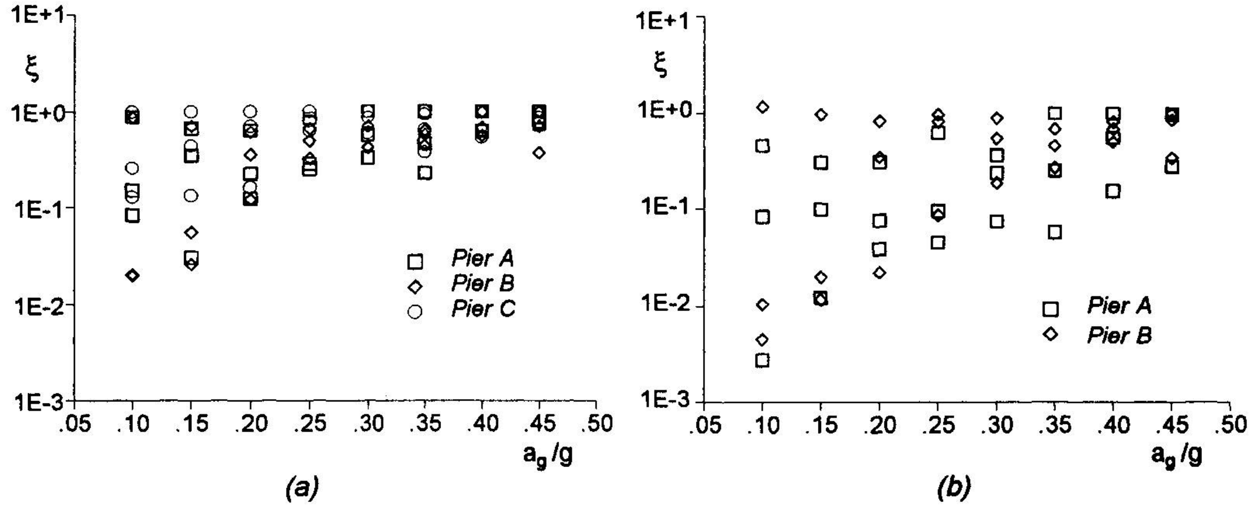

Fig. 1 *Ratio ξ between damage probabilities of the individual piers (upgraded/existing piers) vs. peak ground acceleration: (a) intervention types J1, J3; (b) intervention type J2.*

As for IS interventions, the i/d devices on rectangular piers (bridges 1-5) have been designed with yield strength equal to 50% (Case 1) of the pier limit strength in the transversal direction, and those on circular piers (bridges 6-11) with yield strength equal to 50% (Case 1), 75% (Case 2) and 85% of the pier limit strength. Fig. 2 shows that in this way the damage probability of bridges is usually reduced by one or two orders of magnitude up to the largest values of a_g (ξ_{avg} is equal to 0.056 for Case 1 and to 0.014 for Case 2), even if the devices are placed only on the two stiffest piers; the reduction is much larger for lower values of a_g. If the seismic action acts in the longitudinal direction, the most effective intervention consists in placing only one device on the abutment.

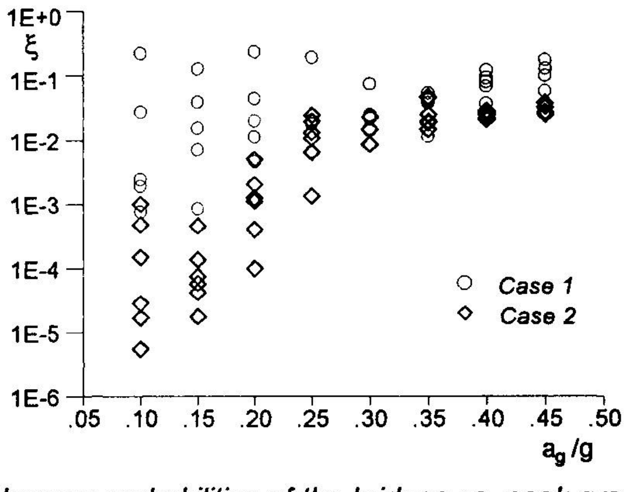

Fig. 2 *Ratio ξ between damage probabilities of the bridges vs. peak ground acceleration (seismic action acting in transversal direction), as a function of the yield strength of the i/d devices .*

From the results of the numerical analyses, it can be inferred that:

- the replacement of existing bearings with i/d devices can eliminate the need for strengthening the piers, but the stiffnesses and strengths of the restraints must be calibrated in such a way that a favourable redistribution of seismic forces between piers and abutments is obtained;
- this intervention is very effective also if the expected seismic intensity is very high and the bridges are characterized by piers of different height: as a matter of fact, it makes more regular the nonlinear response of the whole structural system;
- the yield strength of the i/d devices should be limited to 50 - 75% of the pier limit strength (the lower value apply if the force-displacement relationship of the i/d device may present a signifi-

cant hardening);

- the i/d devices can be placed on the stiffest piers only;
- this intervention permits to eliminate the expansion joints.

3. SEISMIC UPGRADING OF A HIGHWAY NETWORK

Specific reference is made to the seismic reliability of existing road networks, a system modelled in general as a redundant network, comprising a number of critical elements, identified with the bridges in this study.

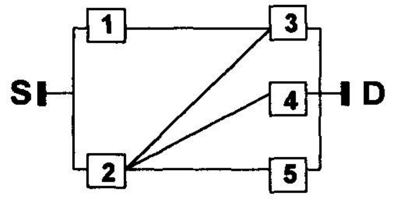

Fig. 3 *Example network*

If C_{max} is the total amount of resources available, its optimal allocation corresponds to the set of interventions (each with a cost H_i) which maximizes the chosen objective function when the network is subjected to an earthquake of intensity a_g, under the constraint

$$\Sigma_i H_i \leq C_{max}$$

As a case example, the bridges 1-5 (Table 1) are located in the five nodes of the network represented in Fig. 3, that is assumed to fail when the connection between the nodes S and D is severed (i.e., the *reliability* R of the network is defined as the probability of maintaining a connection between a *source* and a *destination* node).

Reasonable construction costs of the five bridges, costs and times required by three types of interventions on each bridge (J1, J2, IS, indicated as I, II, III in this Section) and *out-of-service times* (i.e., times required to restore a bridge hit by an earthquake) have been assumed; all costs have been expressed in terms of an ideal *resource unit* (r.u.) equal to 1/100 of the construction cost of bridge 4 [1][2][3].

On the basis of the results summarized in Sec. 2 with regard to the decrease of fragility, the interventions have been optimized with respect to three alternative objective functions [3], namely:(i) the decrease of the above defined probability P_f of network failure (i.e., the increase ΔR of the network reliability); (ii) the ratio (defined *time-efficiency*) $\eta = \Delta R/T^*$ between the increase of network reliability ΔR yielded by a set of interventions and the time T^* that its execution requires; (iii) the length of time (*out-of-service time*) in which an upgraded network remains out of service after an earthquake, i.e., the time necessary to restore at least one S-D path.

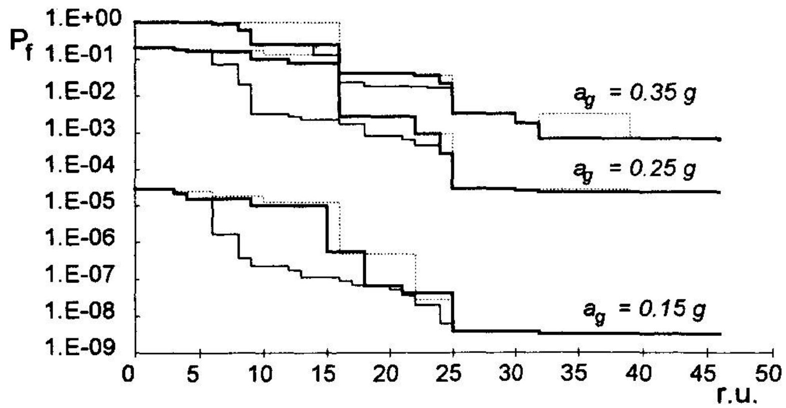

Fig 4 *Probability of failure P_f of example network vs. employed resources, optimized with respect to the probability of network failure itself* (thin lines), *to the time-efficiency of the interventions* (thick lines) *and to the out-of-service time* (dotted lines)

The distributions of the interventions optimized with respect to the three objective functions for a_g = 0.35g are reported in Table 3, while the three sets of lines in Fig. 4 show, for three values of a_g, the corresponding probability of network failure P_f, versus the total amount C_{max} of available resources (note that 46 r.u. are sufficient to perform intervention III on the five bridges of the network).

The first optimization yields of course the lowest probabilities of failure P_f, but all P_f plotted in Fig. 4 can be shown [2] to be much lower than the probabilities obtained with the same amount of resources allocated without optimization. Thus, Fig. 4 proves that alternative optimizations yield comparable results and therefore suggests to find a compromise solution to take account of different exigencies.

	C_{max}	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	46
(i)	1	-	-	-	-	-	-	-	-	III	III	III	III	III	III	III	III
	2	-	I	III	III	III	III	III	III	III	III	III	III	III	III	III	III
	3	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III	III
	4	-	-	-	-	-	-	-	-	-	-	-	-	III	III	III	III
	5	-	-	-	-	I	-	-	I	-	I	III	III	-	-	I	III
(ii)	1	-	-	-	-	-	III	III	III	III	III	III	III	III	III	III	III
	2	-	-	-	-	-	-	-	II	III	III	III	III	III	III	III	III
	3	-	-	-	-	-	-	-	III	III	III	III	III	III	III	III	III
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	III
	5	-	-	-	-	-/I	-	-	-	-	I	III	III	III	III	III	III
(iii)	1	I	I	I	III	III	III	III	III	III	III	III	III	III	III	III	III
	2	-	-	-	-	-	-	-	I	III	III	III	III	III	III	III	III
	3	-	I	I	I	I	III	III	III	III	III	III	III	III	III	III	III
	4	-	-	-	-	-	-	-	-	-	-	I	I	I	I	I	III
	5	-	-	-	-	-	-	-	-	-	I	-	-	III	III	III	III

Table 3 *Interventions on each bridge (1-5) vs. employed resources (3-46 resource units) optimized for a_g = 0.35g with respect to (i) reliability, (ii) time-efficiency, (iii) out-of-service time of the network.*

4. CONCLUDING REMARKS

Two different aspects of the same problem have been briefly tackled in this paper. To improve the exploitation of available resources for reducing the seismic risk (like any other risk) of the constructed world, it is indeed necessary on the one side to understand better the effects and efficiency of upgrading interventions applied to individual structures, on the other side to know how to distribute these interventions among the elements of a system. To give some contributions to this double need has been the object of this and previous papers.

ACKNOWLEDGEMENT Research supported by a grant from the (Italian) National Research Group for Earthquake Effects Mitigation (G.N.D.T.).

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