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Probabilistic damage simulation for strengthening design of concrete structures

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Shape memory alloy (SMA) is a smart material that can be applied as an internal and external reinforcement of reinforced concrete flexural elements in order to increase ductility and strength of the members. Column-beam joint is a critical section of a concrete structure which under seismic and unexpected heavy loads may lead to failure of entire of the structure. Therefore, this numerical investigation aims to increase strength and mitigate risk of failure of the joint by employment of SMA plate. To do so, an experimentally investigated joint under 1000 load combinations has been simulated in Ansys APDL. Each load combo contained two axial loads and one bending moment; load values have been randomly selected through a procedure in MATLAB. Some nodes in plastic hinge region of the joint were chosen as control points. Generated load values were applied in the simulation, and stress of the control nodes was recorded. This process continued for all 1000 combos. Then, obtained results were imported into MATLAB for a probabilistic analysis. Probability of 0.95 quantile of stress of each node was calculated in order to design the required plate thickness at each node. Some numerical examples were applied on the designed plate. Results demonstrated that the designed SMA plate gets the risk of failure from the joint away and increase strength of the joint.

1 Introduction

Reinforced concrete is the most common construction material that has been used for decades in the field of civil engineering. Despite of its low tensile strength, it is still used to build variety of civil engineering structures like bridges and buildings. One of the critical section of the structures that usually lead to failure of entire of the structures is concrete column-beam joint. This section is usually damaged under seismic and unexpected heavy loads. Hence, a strategy should be followed to strengthen the already built joints exposed to new heavy loads and to repair already damaged joints. A promising and novel idea is to use SMA with specific features like self-healing as internal [1] or external reinforcement [2] of the joint. There are two forms of the alloy: (i) Shape memory effect which is sensitive to temperature and (ii) Superelastic shape memory alloy. Second form is the most common and investigable type of the alloy in structural engineering. Author attempts to use probabilistic technique to design and optimize a SMA plate and apply it as an external reinforcement at the joint in order to get the danger of the joint failure away and enhance strength of the joint.

2 Model setup and assumptions

A concrete column-beam joint experimentally investigated by Youssef et al. [1] has been modeled in Ansys APDL. Details of the system are shown in figure 1. The model was symmetric that is why only half of the joint simulated, and symmetric boundary condition was applied. Bottom of lower column was supposed to be fixed and top of upper column was constrained in X-direction. An axial load on top of the column (R1) and two loads at tip of the beam, one parallel (R2) and another perpendicular to the beam cross-section (R3) were applied on the model. Some impactors were modeled at location of each load in order to avoid highly distorted elements and convergence issue. In the first step, verification and validation of the numerical and experimental results were done. Numerical results had a very good compatibility with experiment as shown in figure 3. A mesh size convergence study was done, and accordingly size of all elements set to be 25 mm with shape of 8-node brick. Solid element 65 which has capability of cracking under tensile and crushing under compressive loads has been employed to model concrete material. All other employed elements and material properties are shown in table 1. Furthermore, initial and final stress values of forward phase transformation of SMA set to be 520 and 600 MPa, respectively and initial and final stress values of reverse phase transformation were 300 and 200 MPa. Residual strain was assumed to be 5 percent.

3 Design technique

Based on relationship of R1-R3, three limit state functions were found. Accordingly, 1000 random values for each load; consequently, 1000 load combinations were chosen in order to run probabilistic analysis. First, the model was run without

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Table 1: Elements and material properties

Material	Element	E (GPa.)	ν	Comp strength (MPa)	Tensile strength (MPa)	σ_{yield} (MPa)	$\sigma_{ultimate}$ (MPa)
Concrete	Solid 65	36.6	0.2	53.5	3.5	-	-
Main bars	Reinf 264	198	0.3	-	-	520	630
Stirrups	Reinf 264	198	0.3	-	-	422	682
SMA	Solid 185	62.5	0.3	-	-	-	-
Impactors	Solid 45	210	0.3	-	-	-	-

SMA plate under aforementioned load combos. The most critical one was taken into consideration to design a SMA plate with a uniform thickness. According to result of the first step, a SMA plate with 7 mm was applied in plastic hinge region of the joint. Thirty-six nodes located in external surface of the plate were chosen as control nodes. Stresses of each node for all 1000 load combos were recorded and imported into MATLAB software. A probabilistic study was carried out for each node, fitted distributed was found, and 0.95 quantile of the stresses of each node was calculated and chosen as design stress in order to optimize thickness of the plate. Once the plate's thickness was optimized, its geometry was modeled in Ansys (see Fig. 2), and some numerical examples with random combos were run in order to check whether the optimized plate can still help the system to suffer larger loads.

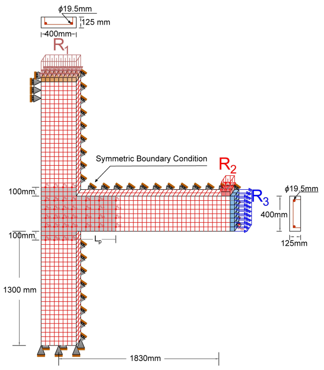

Fig. 1: Column-beam joint

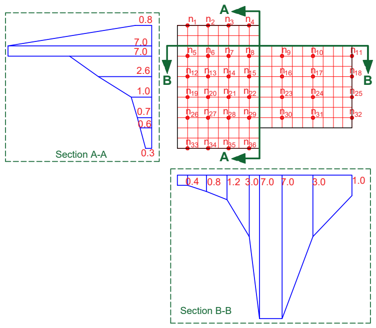

Fig. 2: Optimized plate

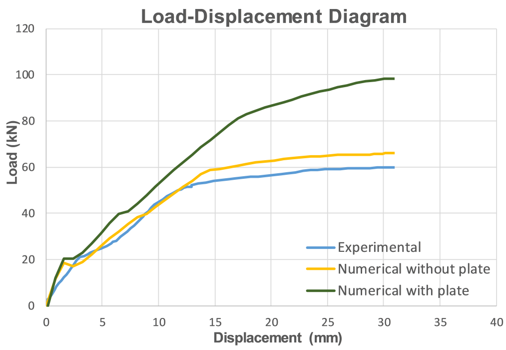

Fig. 3: Load-Displacement diagram

4 Numerical example

As a numerical example, the same load values of experimental investigation (R1=350 kN, R2= 32 mm and R3=0) were applied on the system in order to observe improvement of the system in terms of strength and failure location. The system without plate was considered as benchmark, and the system strengthened with optimized plate achieved from probabilistic study as developed case. Load-displacement behavior of the system corresponding to the system with and without the optimized SMA plate is shown in figure 3. The system without SMA plate started cracking at load R2 equal to 58.8 kN, while the system with the plate was still far from failure, but first crack was observed under load R2 equal to 81.2 kN. Furthermore, in system without the SMA plate, failure occurred exactly at intersection line of column and beam elements, where the failure mode can lead to failure of entire of the structure. However, in case of existence of the plate, location of the failure moved toward middle of the beam, where the plate ended; therefore, danger of failure of entire structure was minimized.

5 Conclusion

This numerical investigation has been done in order to increase strength of concrete column-beam joint with SMA plate and get risk of joint failure away. To do so, a probabilistic study on recorded stress of 36 nodes of the model under 1000 simulations carried out in order to design and optimize SMA plate's thickness. After installation of the optimized plate, some numerical examples were run to check functionality of the plate after optimization. Results showed that the SMA plate not only increased strength of the joint significantly, but also transfer maximum stress of the steel fibers to somewhere close to end of SMA plate length so that even in case of failure, entire the structure will still stay in a safe mode and only beam will be damaged.

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