# SMART shear keys to prevent bridge girders from falling off during earthquakes and tsunami – preliminary numerical simulations

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## *Abstract*

Shear keys play an import role in limiting the excessive displacement of bridge superstructures during catastrophic events. However, rigid shear keys often damage, leading to girders falling off their support as observed during past earthquakes and tsunami. In this study, a Sliding, Modular, Adaptive, Replaceable, and Two-dimensional (SMART) shear key is designed to control the movement of bridge superstructures through earthquake-adaptive friction mechanism. A SMART shear key consists of three concrete blocks and assembly accessories. The three concrete blocks are made of ultra-high performance concrete (UHPC). The assembly accessories include two dowel bars with a diameter of 32 millimeters, two fitting couplers, several nuts, and washers. The SMART shear key will be assembled and installed on the bridge cap beam as an adaptive stopper of bridge girders. Two angled sliding interfaces are designed between the three concrete blocks, so that one block can slide vertically, and another block can slide horizontally with girders when earthquakes shake the bridge. Thus, the sliding feature of the SMART shear key makes the shear key adaptive to the movement of bridge girders, which could significantly reduce the impact between bridge girders and shear keys, and mitigate the structural damage. The shear-resistant mechanism of the SMART shear key is also studied. The SMART shear key transfers the force from girders via two sliding interfaces of concrete blocks and dowel bars. Basically, the dowel action of bars and surrounding concrete, the kink effect of dowel bars and the aggregate interlock form the shear-resistance mechanism of the SMART shear key. To simulate these shear-resistant effects, 3D solid numerical models of the SMART shear key are built, which take the highly nonlinear contact and friction into account. Based on the numerical result, the resistant mechanism of the SMART shear key to the movement of bridge girders can be divided into three phases: Slide, Contact, and Yield. In the Slide phase, the shear resistance is mainly from the friction between concrete blocks and the resistant force is almost linearly increasing with the sliding distance. In the Contact phase, the gap between dowel bars and the UHPC concrete blocks is closed. The kink effect of the dowel bars emerge and there is a dramatically increase of the shear resistance in a very short of displacement. In the Yield phase, the dowel bars start to yield due to the contact effect. A plateau of the shear resistance can be seen in this phase due to the ductility of the dowel bars. Overall, the Slide phase helps the SMART shear key to adapt to any initial movement of girders while the Contact and Yield phases help to constrain the movement of girders, thus preventing the girders from falling. The force-displacement curves obtained from the numerical simulation show the capacity of two SMART shear keys with different dimension designs. The larger shear key has a resistance limit at 800kN while the smaller one has around 500kN. The SMART shear key with a good adaptability to the movement of bridge girders and a good capacity to constrain the excessive movement of bridge girders can significantly mitigate the structural damage of bridges in earthquake/tsunami attacks.

*Keywords: SMART shear key, shear-resistant mechanism, numerical analysis, force-displacement curve, adaptability*

## 1. Introduction

According to the earthquake/tsunami reconnaissance reports in the past [1-4], excessive movement of bridge girders caused severe structural damage to bridges. Bridge girders might largely rotate, translate, and even fall down from the cap beam due to failures of bearings or existing shear keys. Given the important role of shear keys to structural performance of bridges in natural hazards, many efforts have been made to develop more efficient shear keys in the past decades [5-9]. However, in terms of the interior shear keys for girder bridges, currently the common one is that the concrete shear key shown in Fig. 1, which is casted into the bridge cap beam so that the concrete shear key can barely move. When the bridge girders move to the concrete shear key, a hard contact and impact will be generated because the concrete shear key is unable to adapt to the movement of bridge girders. So structural damage between bridge girders and the concrete shear key will follow. Besides, the cast-in concrete shear key can only restrain the lateral movement of the bridge girders while bridge girders may also move vertically observed in the 2005 Hurricane Katrina disaster [1]. Therefore, a novel SMART shear key is proposed in this paper to address the disadvantages of the existing concrete shear key [10]. The detailed design of the SMART shear key is shown in Fig. 1. Concretely, the SMART shear key consists of three modules: Module I, Module II, and Module III. Between Module I and Module II there is a sliding interface, and between Module II and Module III there is a sliding interface. The three modules are assembled with dowel bars as a whole shear key. The whole shear key is installed next to the bridge girder through couplers and precast anchor bolts. The two sliding interfaces both have an angle of 5º, so the tension forces in the dowel bars will increase when the concrete blocks slide, thus increasing the shear resistance. When the dowel bars contact the concrete blocks, the dowel bars will kink and furtherly increase the shear resistance until the bars start to yield, so that the shear key can adapt to and at the same time restrain the movement of bridge girders.

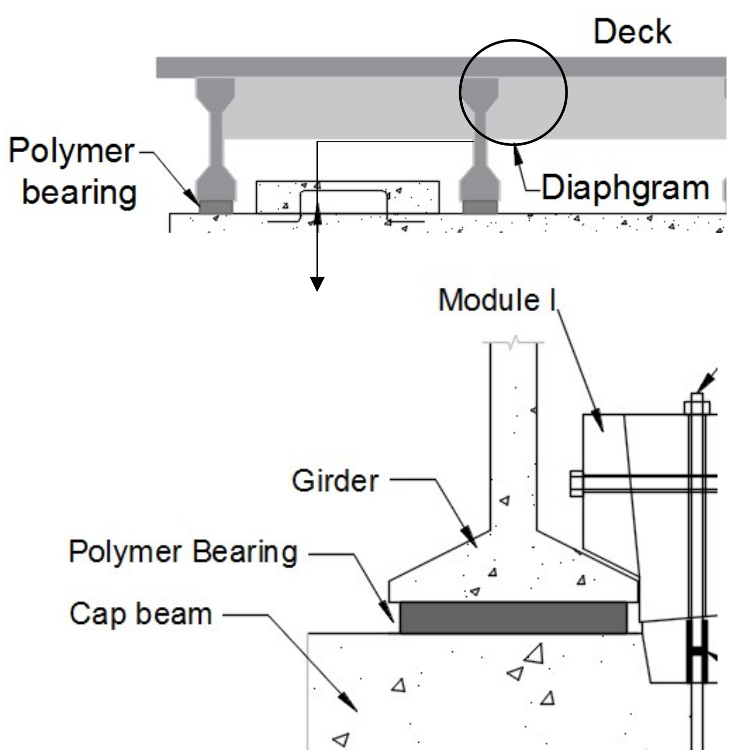
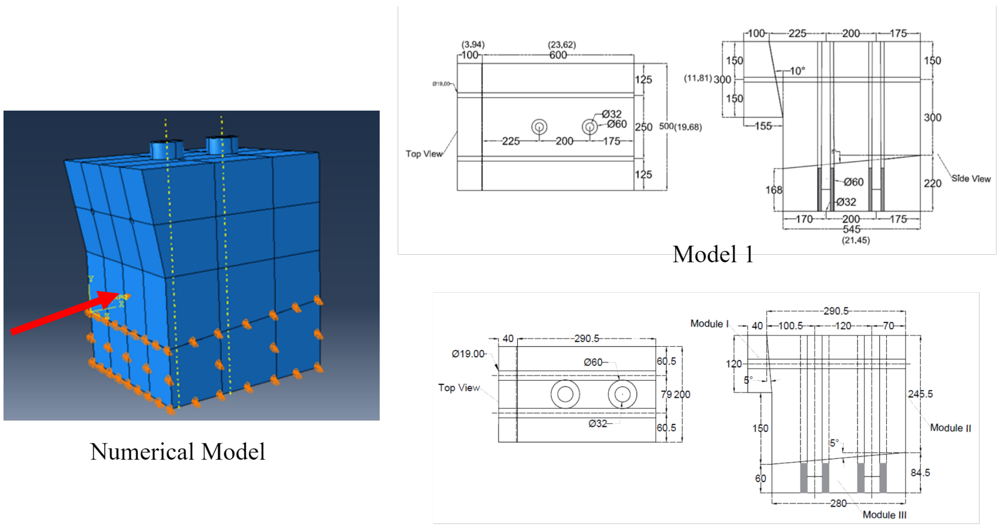



Fig. 1. Schematic sketch of the concrete shear key and SMART shear key

## 2. Numerical models of the SMART shear keys

It was investigated that the dowel action between bars and surrounding concrete [8], the kink effect of bars [11] and aggregate interlock [12] form the shear-resistance mechanism of the SMART shear key [10]. These three highly nonlinear factors are captured and simulated in a commercial finite element software. Two numerical models of the SMART shear keys with different sizes are built via the software. The numerical model and the dimension designs are shown in Fig. 2. The main difference between Model 1 and Model is that Model 1 has larger dimension than Model 2. The vertical dowel bars of Model 1 and 2 are both 32mm in diameter. The dowel bar holes are both 60mm in diameter. The angles of the sliding interface are both 5º. Larger dimension means thicker concrete cover to the dowel bars.




Model 1

Numerical Model

Model 2

Fig. 2 SMART shear key numerical models with two different dimensions

The numerical model is built by 3D solid elements. Only the horizontal movement of Module II against Module III is considered here because the vertical movement of Module I against Module II has the same resistant mechanism. According to the report [13], the compression yield strength of ultra-high performance concrete is set as 100 MPa, the elastic modulus is 42000 MPa and the Poisson ratio was 0.19. The yield strength of the dowel bars is set as 600 MPa, the Yong's modulus was 200000 MPa and the Poisson ratio was 0.3, given the available dowel bar products. The perfect elastic-plastic constitutive models are adopted to simulate the nonlinearity of the ultra-high performance concrete modules and dowel bars.

Module III is fixed in the numerical model and a displacement load is applied to Module II as shown by the arrow in Fig. 2. The general contact method is selected to simulate the contact between dowel bars and concrete block, the friction between Module II and Module III with a friction coefficient of 0.3, and the assembly effect of the steel accessories. The concrete modules and steel bars of Model 1 with the larger dimension are meshed with an element size of 30mm. The concrete modules and steel bars of Model 2 with the smaller dimension are meshed with an element size of 10mm. The explicit dynamic analysis is run to simulate the quasi-static analysis and obtain the force-displacement relationship of the SMART shear keys. The results are compared with the standard static analysis result in [10]. The advantage of the dynamic explicit procedure over the implicit static procedure is that it is easier for dynamic explicit procedure to resolve the complicated contact problems [14]. Quasi-static analysis can model the process of the SMART shear key being pushed in the shortest time period in which inertial forces remain insignificant, thus obtaining close results to those of static analysis.

## 3. Numerical results

As mentioned above, displacement loads are applied on Module II shown in Fig. 2. For the larger Model 1, the displacement loads are 40mm and 60mm within 2s respectively, to study the ductility of the SMART shear key. For the smaller Model 2, the displacement load is only 40mm within 2s. The result is shown in Fig. 3. It shows that Module II of the SMART shear key slides against Module III when the displacement load is applied.

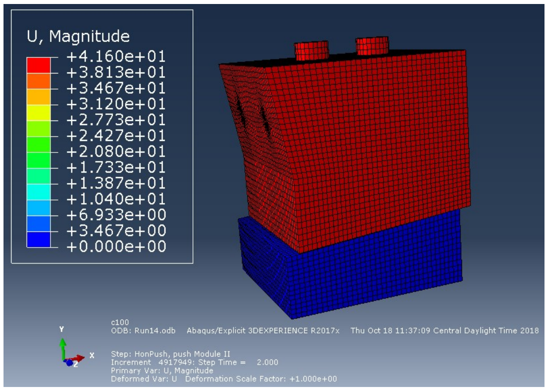



Fig. 3 Module II sliding against Module III of the SMART shear key

Fig. 4 shows the force-displacement curves of SMART shear keys under static and quasi static numerical analysis. It can be clearly seen that the force-displacement curves can be divided into three stages: the Slide stage, the Contact stage, and the Yield stage. The SMART shear key is assembled by two vertical dowel bars with a diameter of 32mm and through two reserved holes of 60mm, thus leaving a gap between the dowel bars and the concrete block with around 14mm wide. Therefore, before the dowel bars contact the concrete and close the 14mm gap, it is mainly the friction force, i.e., the aggregate interlock between the sliding surfaces come into action to resist the horizontal movement of the shear key Module II. And the Slide stage shows a nearly linear increase of the friction force. At around 14mm, the dowel bars start to contact the concrete in the holes, and the bars start to kink very quickly because of the contact. There is a dramatically increase of the shear resistance because of the kink effect of the dowel bars in the short Contact stage. Afterwards, the dowel bars start to yield but maintain very well the capacity to restrain the horizontal movement. Fig. 4 shows exactly how the SMART shear key can adapt to meanwhile sustain the resistance to the movements of bridge girders in Earthquake/Tsunamis attack.

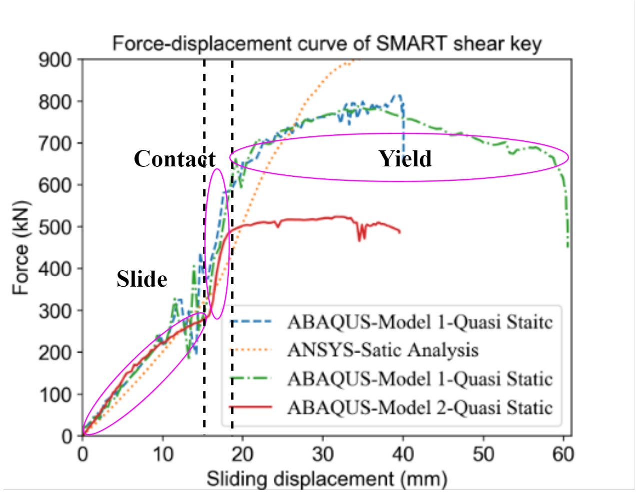



Fig. 4 The force-displacement curves of SMART shear keys under static and quasi static analysis

## 4. Conclusion

To better understand the resistant mechanism of the newly proposed SMART shear key, static and quasi static analysis is conducted with numerical SMART shear key models of different dimensions. The force-displacement curves of SMART shear keys under horizontal displacement loads are obtained. Given the force-displacement curves, the resistant mechanism of the SMART shear key can be divided into three stages: Slide, Contact, and Yield. The Slide stage makes the SMART shear key adapt the movement of bridge girders well. The Contact and Yield stages sustain the ability of the SMART shear key to restrain the movement of bridge girders. Overall, the novel design makes the five features of the SMART shear key: sliding, modulus, adaptive, replaceable, and two-dimensional. Experiments are ongoing to furtherly validate the design of the SMART shear key.

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