Finite Element-Smeared Crack Combined Algorithm based Bridge Corbel Analysis

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Abstract. A practical combined algorithm for the corbel of common reinforced concrete bridge is put forward. Based on material nonlinearity, combining the professional finite element software Midas Civil and MIDAS FEA with Smeared crack model, the Thorenfeldt and Constant curves are used as concrete compression and tension constitutive model to numerical analyze the corbel’s stress and crack. Example results show that the normal stress of the corbel and crack are greater than design value of C35 concrete tensile strength, and part areas are in the plastic state. The groove corner region of the corbel has abrupt stress. The crack of the corbel is firstly generated at the groove and the top plate, and gradually expands with the increase of the load coefficient. It develops sufficiently in the groove region, but there is not any full-length crack. The corbel has a group-strip-like crack farther from groove corner region. The calculation results are consistent with the bridge disease condition, which shows that Finite Element-Smeared Crack Combined Algorithm proposed in this paper is effective for the analysis of corbel.

1. Introduction
With the rapid development of bridge construction, hybrid girder bridge is increasingly used in practical projects and has a good development prospect. For example, hybrid girder cable-stayed bridge has been favored by countries such as Europe and Japan since it appeared in the 1970s[1,2]. At present, most of the steel girder and concrete girder that have been built all over the world are connected by the specially designed steel-concrete composite segment. However, in old-style steel-concrete composite continuous beams bridges, there is no transition section. The concrete section is generally set with the corbel instead of the transition section and steel box girder is erected on the corbel. This paper analyzes the stress and crack of the corbel based on the E ramp of inner loop in Guangzhou city.

2. Analysis of Algorithms

2.1. Constitutive Model

2.1.1. Smeared Crack Constitutive Model. The Smeared crack model is based on the inelastic cracking and strain equivalent. It meets the conservation of fracture energy by adjusting the constitutive relations of material softening[3]. Zhou Lin-ren and other scholars[3-6] studied on crack occurrence
and development of concrete with smeared crack model. Smeared crack model can simulate multiple cracks with high computational efficiency, its constitutive model is shown as figure 1.

![Smeared Crack Model](image1)

**Figure 1. Smeared Crack Model.**

2.1.2. Concrete Compression and Tension Constitutive Model. Thorenfeldt curve is used as concrete compression constitutive model. It can simulate compression failure well, such as the softening of concrete compression, stress-strain downward trend. Constant curve is used as concrete tension constitutive mode.

2.2. Finite element Model Approach.
The composite beam bridge finite element model is established by MIDAS CIVIL, and the concrete corbel model is established by MIDAS FEA. The load value of corbel comes from the composite beam bridge model and is applied to the reinforced concrete girder bridge mode.

3. Case Studies

3.1. Engineering Situation.
The E ramp is a hybrid girder bridge, consisting of composite beam bridge and concrete continuous beams bridge. The composite beam bridge’s total length is 39.38m. It’s calculated span is 38.58m and deck width is 7.06 meters. The total height of the beam is 1.33m, with 100mm thickness bridge deck, connecting by the shear connector. The concrete beam bridge’s span combination is 24+20+20.2 3+22+22.14m and the total height of the beam is 1.4m. The top width of the box girder is 7.3m~14.0m, the bottom width is changed from 2.5m to 9.54m. There is a variable section.

![Composite and Concrete Beam](image2)

**Figure 2. Corbel elevation.**

3.2. Finite Element Analysis.

3.2.1. Composite Beam Bridge Model. The whole finite element bridge model has 42 elements, 43 nodes which is erected by MIDAS CIVIL, and its main beam adopts steel-concrete composite beam. The elevation drawing of composite beam bridge finite element model is shown as figure 3, the middle span section is shown in figure 4. Before the bridge deck is activated and getting stiffness according to the construction stage, its load is carried by the steel box girder. This example is used the stress of the main beam to judge whether the external load of the corbel is correct or not.
3.2.2. Common Reinforced Concrete Box Girder Bridge Model. If only corbel model is erected, it’s necessary to analyze and prove the equivalent processing for its boundary and load to ensure that the finite element analysis result is consistent with actual boundary condition of the corbel. In this paper, a full reinforced concrete bridge model is established to avoid the equivalent processing of the corbel’s boundary and load. The mesh generation is automatic with a high-precision eight-node hexahedron element. The total number of nodes is 132354 and the element number is 150846. The finite element model is shown as figure 5.

The corbel’s finite element model is shown as figure 6, in order to couple with the adjacent beam nodes, matching the adjacent faces and the same unit size as the adjacent beam segments are set when meshing. It checks the grid quality by Warping, Jacobi, ratio of side, twist angle and other parameters. Steel bar and concrete will be coupled automatically by using the software’s steel bar element and there is no slip between steel and concrete. The full-bridge three-dimensional model analyses the influence of the dead load, live load, temperature, and external load on corbel.

1) Basic Assumptions and Calculation Parameters
The example has not established contact relationship between steel and concrete, and they are no slip. The basic assumptions are as follows[7]: small deformation, consider material nonlinearity, isotropic.

The superstructure’s concrete strength grade, elastic modulus, poisson ratio, bulk density is C40, 3.15×10⁴MPa, 0.2 and 25KN/m³ respectively. The steel strength grade, elastic modulus, poisson ratio, bulk density is HRB335, 2.06×10⁵MPa, 0.3 and 76.98KN/m³ respectively.

2) Load Application
System temperature and temperature gradient are applied by node temperature, and the temperature gradient is formed according to code[8]. Secondary load is applied in three steps. Lane loading is applied to the most unfavorable load position with static load. It gets the corbel’s external load value from the composite beam bridge model, and it is applied by the mean of surface pressure to avoid stress concentration happening. The most disadvantageous load combination for superstructure’s superior margin is condition I: dead load+secondary load+live load+positive temperature gradient+positive system temperature; The most disadvantageous load effect combination for superstructure’s lower margin is condition II: dead load+secondary load+live load+negative temperature gradient+negative system temperature.
3.3. Analysis of Results.

3.3.1. Stress Analysis. 1) Stress Reaction of Composite Beam Bridge

The results of the maximum and minimum main girder stress under the most disadvantageous load effect combination is shown in the figure 7 and table 1.

Table 1. Stress checking(Unit: MPa).

| Location | Max/Min Stress Value In The Code | Remark |
|----------|----------------------------------|--------|
| Steel Box Girder | Superior Margin: -183 | 275 | Positive values is tensile stress, and negative values is compressive stress |
| Concrete Slab | Superior Margin: -11.4 | 18.4 |
|             | Lower Margin: 208 | 275 |
|             | Lower Margin: -9.4 | 18.4 |

According to the above figure 10 and table 1, the maximum and minimum stress of the steel box girder occur at the mid-span as well as the Min stress of the deck, but bridge deck’s stress changes little along the bridge span on the superior margin. All of them meet standard[9].

2) Corbel Analysis

Modified Newton-Raphson method is used to solve this model. Computer will stop analysis when it does not converge or exceed the maximum number of iterations. The example is stopped when the load factor of conditionⅠis 0.8 and the load factor of conditionⅡis 0.7. It means that the structure is destroyed under 80% and 70% load.
The normal stress distribution of the corbel is shown in figure 8 and figure 9. The stress on the corbel is symmetrical distribution and it has compressive stress in load action area. Other areas are mostly tensile stress, especially at the groove and top plate. Some of them are out of the standard’s allowable value[10]. From the stress nephogram, there is abrupt stress at the groove area in the corbel.

3.3.2. Crack Analysis. The total strain model which belongs to smeared crack model is adopted. That is, total strain is used instead of separating various strains and the crack’s tension-compression is used in a different stress-strain relationship. The paper has detailed analysis based on the effect of condition I.
The groove and top plate are in a plastic state, because it occurs to tensile stress and the value is more than allowable value. The plasticity is spread from the groove to the surrounding, and it becomes serious at the loading plant zone.

When the load factor is 0.3, the crack is first generated at the groove of the corbel. With the increase of the load factor, the crack gradually expands to the periphery. The top plate of the corbel is under tension when the load factor is 0.3, because of the effect of bridge deformation. When the load factor is 0.8, most area is cracked during loading, but there is no full-length crack, and the white area shows that it has not cracked.

Knowing from the figure 12, great majority crack’s normal stress is greater than design value of tensile strength of concrete. The place marked by a circle means that there is a crack, and its direction is consistent with the circular plane. Circle’s size reflects crack development condition. A large number of three-dimensional orthogonal wafers are distributed at the groove of the corbel, and it means that concrete crack has fully developed. At an angle of about forty-five degrees with the horizontal, it distributes some ribbon-type crack. Therefore, it is necessary to enhance the confinement effect, prevent the further development of cracks, and meet the requirements of serviceability by improving the layout and quantity of reinforcement in this area. The above analysis results are consistent with the actual bridge disease situation, which show that the combined algorithm proposed in this paper is reasonable and feasible. With the resistance of the material attenuation, load-carrying capacity of the corbel will decrease. Analysis of the corbel should be studied furtherly in order to obtain a more objective analysis results based on the material attenuation factor[11].

4. Conclusion and Prospect

Thorenfeldt and Constant curves are used as concrete compression and tension constitutive model. The calculation results of MIDAS CIVIL is applied as an external load of MIDAS FEA model. Based on Smeared crack model, the stress and crack of the corbel are analyzed by building the hybrid beam corbel’s three-dimensional model using MIDAS FEA. The article proposes a practical algorithm for the analysis of hybrid beam corbels and gets the following conclusion: 1) It occurs to abrupt stress and has stress difference at the groove of corbel. The tensile stress in most areas has exceeded the allowable value of the code. These results lead to accelerating the emergence and development of crack. Corresponding measures should be taken to reduce the occurrence of abrupt stress. 2) The crack of corbel is simulated and analyzed on the basis of material nonlinearity. Through analysis, the crack is produced at the groove of the corbel and at the roof firstly, and gradually expand to the surrounding with the increase of the load factor, but there is no full-length crack. 3) Under load action, the groove is in a plastic state firstly. With the increase of load factor, the crack is fully developed. At an angle of about 45 degrees with the horizontal, it distributes some ribbon-type crack. Therefore, it is necessary to enhance the confinement effect, prevent the further development of cracks, and meet the requirements of serviceability by improving the layout and quantity of reinforcement in this area. The above analysis results are consistent with the actual bridge disease situation, which show that the combined algorithm proposed in this paper is reasonable and feasible. With the resistance of the material attenuation, load-carrying capacity of the corbel will decrease. Analysis of the corbel should be studied furtherly in order to obtain a more objective analysis results based on the material attenuation factor[11].
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