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Analysis of Elasto-plastic Contact with Coating Surface of Weathering Steel of Fabricated Supports and Hangers

Libo Mai, Hehui Wang*

School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, China

*Corresponding author e-mail: 13127966362@163.com

Abstract. Three-dimensional elasto-plastic behaviors of NiCoCrAlY coating under the indentation contact of rigid indenter are studied by using the finite element method, and the distribution of stress at the interface is analyzed. The influence of the coating of the weathering steel on the substrate material properties is studied when it is squeezed by the elastic pipe, and then the loading condition of the weathering steel is checked. The results show that the NiCoCrAlY coating can effectively improve the contact bearing capacity of the surface of the weathering steel, and there comes obvious residual deformation and stress in the coating entering the plastic stage after unloading. In addition, the compressive stress and the shear stress at the interface are mainly concentrated in the pressure center, and they will also increase with the increase of load. Eventually, the rationality of the design of the standard atlas of fabricated supports and hangers is verified.

1. Introduction

Surface coating technology can improve the properties of the substrate material, such as anti-wear, anti-corrosion, and significantly prolong the service life of components. Therefore, the coating/substrate system has been widely used [1], which has great significance in the industry. The coating and substrate have different elasto-plastic properties, and they have different stress state and deformation under a concentrated force. In general, the finite element method can provide a helpful solution to elasto-plastic contact problem. Zhao Hua [2] used the virtual contact load method to study the elasto-plastic contact problem of the thick coating. Kral [3] and K. Hayashi [4] used the finite element method to analyze the stress state of various coating structures.
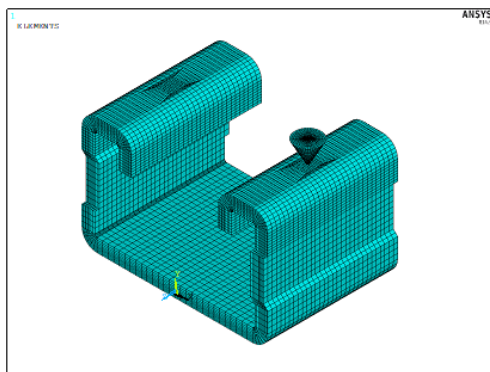
The commonly used C type steel of fabricated pipe supports and hangers in buildings is usually selected as the analysis object because of its excellent engineering practicability. Most domestic pipe supports and hangers are made of Q235B with hot-dip galvanized surface. However, they cannot meet the requirements of the design life of the pipe gallery which is usually up to 100 years [5]. To extend
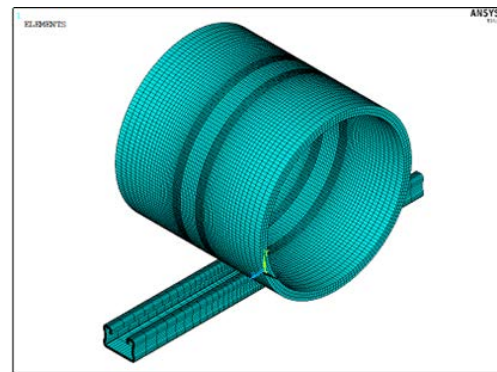
the service life of supports and hangers, the weathering steel with good weather resistance and paintability is selected as research object (GB/Q345NQR2), and the surface adopts NiCoCrAlY coating which can improve the corrosion resistance of the substrate. The elasto-plastic analysis is carried out by indentation method to analyze the stress distribution of the coating on weathering steel under the squeezing state of the diamond cone. Meanwhile, the effects of displacement loading on the plastic deformation of the coating has also been studied. By using ANSYS, the working condition of supports and hangers with the 3m gap is simulated to study the influence factors of coating on the substrate properties. Besides, the atlas of supports and hangers is checked. The results of the study provide technical support for the design and selection of coatings, which can effectively improve the life of steel.

2. Finite element mold

Referring to the architectural standard atlas *Selection and Installation of Fabricated Indoor Pipe Supports and Hangers* [6], SC-25 type steel is selected to establish a geometric model with 1mm coating in ANSYS. The tip of the indenter is 0.3mm radius spherical. In the finite element calculation, the contact model adopts area-area contact type and 3D 20-node isoparametric quadratic element. It is worth noting that the mesh of the contact area is refined to ensure the calculation accuracy of the contact position. The indenter and pipe respectively contact with the coating/substrate system, which is shown in Fig. 1 and Fig. 2. Considering the local plastic deformation of the contact position, the materials of the coating, the substrate, the pipe all adopt the classical bilinear kinematic hardening constitutive relation. The main material parameters are listed in Table 1 [7].

Figure 1. Finite element model of C type steel with indenter loading.

Figure 2. Finite element model of C type steel with pipe loading.

Table 1. Material parameters.

	Indenter	Coating	Substrate	Pipe
Material	diamond	NiCoCrAlY	Q345NQR2	Q235
Elasticity modulus/GPa	1100	168	210	206
Poisson's ratio	0.07	0.35	0.28	0.3
Yield strength/MPa		632	525	235
Strengthening modulus /GPa		1.68	2.1	2.06

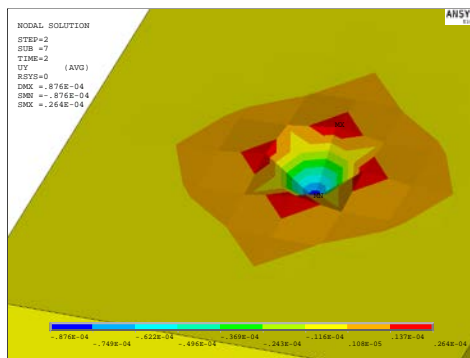## 3. Finite element contact analysis of indenter loading

3.1. Elasto-plastic analysis

In the finite element model of indenter load, the contact calculation between the indenter and the coating is used to simulate the process of indentation experiment. The whole calculation process contains three stages: firstly a displacement load U_y = -0.10mm is applied to the top surface of indenter to produce elasto-plastic deformation of the coating; then the residual deformation and stress after removing displacement load are observed; eventually, a displacement load U_y=-0.08mm is applied.
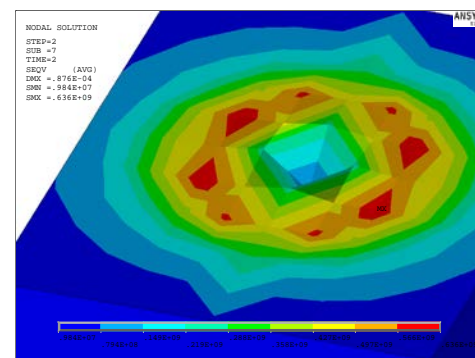
The stress-strain data of elasto-plastic analysis obtained in the simulation are shown in Table 2. It can be found that the maximum stress of the coating is 688Mpa after the first stage which is higher than the yield strength of the coating material. At this duration, the coating enters the hardening stage and generates a plastic strain of 0.157446. The maximum stress in substrate does not exceed the yield strength. Therefore, no plastic strain originates.

Table 2. Stress and strain data.

Load step	Coating			Substrate		
	σ_{max}/ Mpa	ε^p	ε^e	σ_{max}/ Mpa	ε^p	ε^e
1	688	0.00533	0.157446	454	0.002217	0
2	636	0.00402	0.157446	191	0.001034	0
3	528	0.00352	0.146053	187	0.001060	0

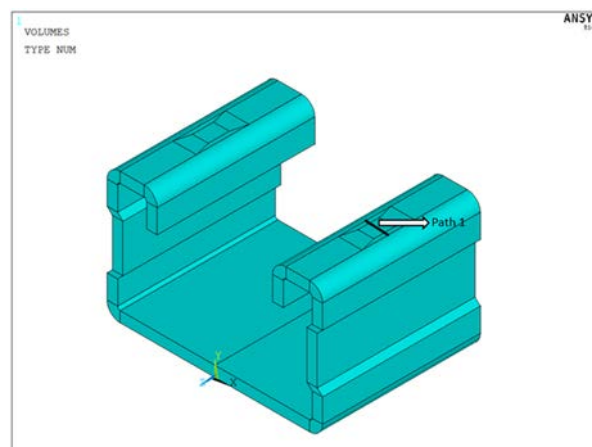**Figure 3.** Displacement of the   partial coating after unloading.

Figure4. Von Mises equivalent stress of partial coating after unloading.

After unloading, it's found that the maximum stress and elastic strain of coating decrease slightly while the plastic strain stays the same, but the maximum stress and elastic strain of substrate decrease obviously. The coating begins to enter the plastic phase when the displacement loading of 0.1mm is taken, and the coating produces residual deformation and stress after unloading. The local displacement and stress of the coating after unloading are shown in Fig. 3 and Fig. 4. According to the figures, there produces obvious indentation at the contact position, and a small number of bumps come into being along the edges. Meanwhile, a stress concentration is obvious at the bottom and inner edge of the indentation. Since the material is strain-strengthened, and the secondary loading is smaller
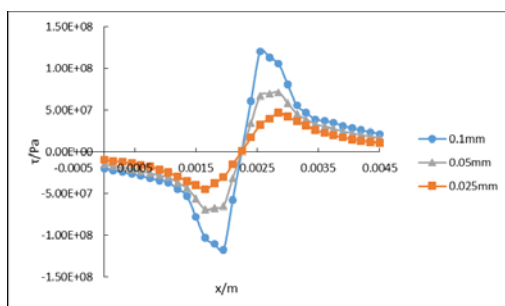
than that of first, the coating maintains shakedown phase without generating a new plastic strain, which is equivalent to linear elastic deformation.
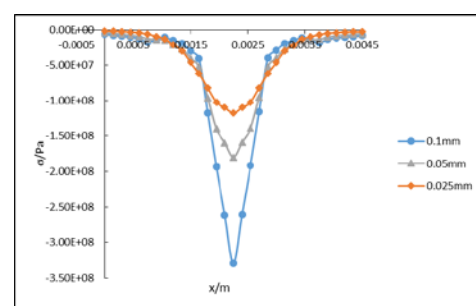
3.2. Interfacial stress analysis

To analyze the distribution of stress at the bonding surface between the coating and substrate under displacement load, the interfacial shear stress and normal stress between the coating and the substrate are observed. According to Fig. 5, the nodes at the bonding surface of the contact center are selected to form the path. As are shown in Fig. 6 and Fig. 7, the normal stress and shear stress data on the path are extracted when the displacement loads are U_y =-0.025mm, U_y =-0.05mm and U_y =-0.10mm. The shear stress and normal stress are symmetrically distributed with the pressure center, but the maximum shear stress appears near the pressure center and the normal stress is at the pressure center. The normal stress exists mainly in compressive stress, which indicates that the coating and substrate near the interface are squeezed. The maximum interface shear stress and compressive stress both increase with the increase of the indentation depth. At the beginning of loading, the maximum shear stress and compressive stresses are only 46.8Mpa and 117Mpa, and when the displacement load increases to 0.1mm, the values of the shear stress and the compressive stress reach 121MPa and 330Mpa respectively.

Figure 5. Path location.

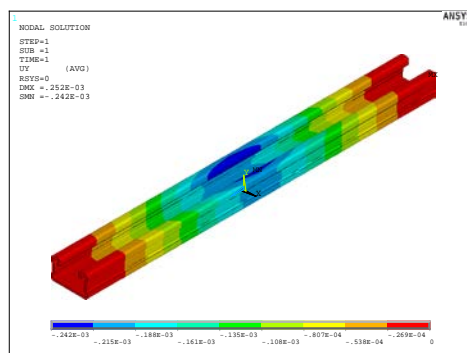**Figure 6.** The shear stress distribution at the interface with different indentation depths.

Figure7. The compressive stress distribution at the interface with different indentation depths.
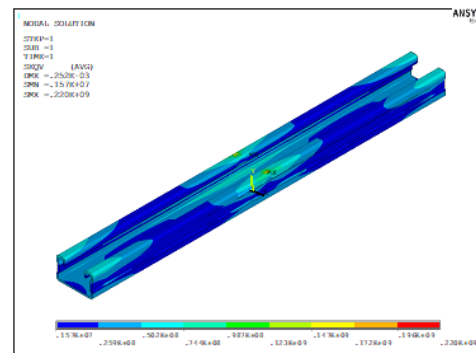
4. Finite element contact analysis of pipe loading

According to the design standard of SC-25 type steel [6], a set of data are selected for finite element analysis and calibration. The selected parameters are as follows: non-insulated pipe DN200, C type steel length 400mm, supports and hangers spacing 3000mm, and total mass 290kg. Because the stress state at the contact position between the pipe and weathering steel is the key factor and the influence of the pipe length is less important, a simplification is adopted that the pipe length is set 200mm. The pipe equivalent density for gravity loading is $2.31 \times 10^5 kg/m^3$ which originates from the total mass of the pipe and the simplified pipe volume.

The analysis results of the contact model between the pipe and the C type steel show that the maximum stresses of pipe and coating are 129MPa and 581MPa respectively, which are both lower than the yield strength of the material, so the strength requirements are met. The displacement and stress of the substrate are shown in Fig.6 and Fig.7 respectively. The maximum displacement of the pipe occurs in the middle of substrate with a value of 0.242mm. Obviously, the stiffness requirement is also met because the maximum displacement is less than 1/200 of the span of the beam. Meanwhile, the maximum stress of substrate is 220MPa, which is less than the yield strength of the substrate material. In general, the allowable stress is obtained by dividing a safety factor. In this calculation process, the allowable stress of the substrate is 350Mpa by setting the safety factor as 1.5. Therefore, the substrate meets the strength requirement, and the beam is safe as well when the distance between the supports and hangers is 3m.

Figure 8. Displacement of the substrate.

Figure 9. Von Mises equivalent stress of the substrate.

The beam element model and material mechanics calculation are used to analyze the stress of the beam when the distance between the supports and hangers is 3m. The maximum displacement and stress of the beam element model are 0.297mm and 109MPa respectively. The maximum deflection and normal stress of the beam are 0.228mm and 103.9MPa which are calculated by material mechanics. The maximum displacement and stress calculated by the two methods are almost equal. Both the strength and stiffness meet the requirements of the material, so the safety of the beam is verified more rationally.

The finite element model of the uncoated beam under pipe loading is also analyzed by using the solid element. The results show that the maximum displacement and stress are 519MPa and 0.403mm respectively, which differ greatly from the data obtained from the beam element. Errors come from the

fact that the plane assumption of Euler-Bernoulli classical beam theory on which the beam element is based only considers bending stress during bending deformation. Therefore, the beam element model cannot truly reflect the local stress concentration and deformation at the contact position between the beam and pipe.

5. Summary

The elasto-plastic coating, the stress distribution at the interface and loading condition of SC-25 type steel are analyzed by using the finite element method, and the following conclusions are drawn: 1) After entering the plastic stage, there is obvious indentation on the coating if the load is unloaded, a small number of bumps appear at the edge of the indentation and the stress concentration is obvious at the bottom. 2) The compressive stress and the shear stress at the interface increase with the increase of load when the indenter is squeezed, and the maximum stress is located at the pressure center. 3) The load carrying capacity of the coating/substrate system is much better than that of the uncoated substrate, indicating that the coating can effectively protect the substrate and extend the service life of parts. 4) The safety of weathering steel is verified when the supports and hangers spacing are 3m, which is consistent with the standard atlas design of fabricated supports and hangers. 5) The finite element analysis of beam element cannot more realistically reflect the local stress concentration at the contact position between the beam and the pipe, while the solid element can effectively calculate the actual results.

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