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Study on the cumulative damage of a transmission tower under seismic wave excitation

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Abstract

The structural response of a steel angle tower considering the effects of material damage under earthquake excitations is simulated and analyzed in this paper. In consideration of the damage accumulation effect, a simulation of the steel angle tower under strong earthquake motions is performed. The necessity of a structural damage analysis is reflected by the comparison of the structural response with and without considering the material damage effect. This result could provide evidence for the safety assessment of steel angle towers and reconstruction after disasters.

Keywords: steel angle tower; response analysis; the material damage effect

1. Introduction

In recent years, material damage has been the focus of studies on structural performance. The effects of material damage on structural performance have been continuously analyzed by researchers. Over the past few decades, numerous studies have been performed on the damage accumulation effect and structural response. Using an 8-story steel frame structure as an example, Kong et al [1] proposed a numerical simulation method for the collapse of a steel structure under rare earthquake conditions based on the material damage and failure laws and verified its validity. The dynamic responses and failure modes of the steel column and plane steel frame under blast loading were analyzed by Li et al [2] considering the strain rate and the cumulative damage effect. Ding et al [3] studied the seismic action considering a damage accumulation space truss structure bomb under the effects of plastic responses. The results indicated that including the damage accumulation effect of a spatial truss structure on the elastic plastic seismic response has a significant impact. Based on the fracture energy and stiffness degradation, Lee J et al [4] introduced a new plastic damage model of concrete under cyclic loading and verified its effectiveness. The dynamic responses of concrete structures under different loading speeds were simulated by Li et al [5] using a concrete dynamic constitutive model in ABAQUS, and the ability to simulate the dynamic properties of concrete using a damaged plasticity model was evaluated. The structural responses of transmission towers under earthquake excitations have been studied thoroughly. However, there are few research on the seismic response of transmission towers and the effect of the material damage. Similar to typical high-rise structures, transmission towers are sensitive to natural disasters. It is necessary to study the effects of the damaged pole pieces on the performance of transmission towers.

In this paper, the seismic action considering the material damage cumulative effect of a steel transmission tower to a seismic response is simulated using finite element analysis software ABAQUS. Based on the cumulative damage, the effects of the component part of the angle damaged under strong earthquake conditions on the overall performance of the transmission tower are analyzed. A comparative analysis of the transmission tower with and without considering the cumulative effect of the material damage response is performed, i.e., considering the necessity of the material damage accumulation effect. The results can provide a basis for the evaluation and repair of the transmission tower.

2. Damage model of the steel material

A few elements of the steel structure reach the yield limit under earthquake excitations. During seismic loading, certain elements will enter the plastic phase, and phenomenon such as stiffness degradation and plastic deformation will occur due to the accumulation of the material damage. Then, the elements lose their load-bearing capability, and the structure collapses. Different damage models result in different structural responses. An appropriate damage criteria is the key to exploring the effects of the damage cumulative effect on the dynamic response of the transmission tower.

The damage analysis of the transmission tower subjected to earthquake excitation is conducted using the finite element analysis software ABAQUS. The initial criterion and damage evolution need to be determined in ABAQUS. Fig. 1 illustrates the stress-strain curve when material damage occurs. After an element reaches ultimate strength, the elastic modulus and stiffness will decrease with a continuous increase in the plastic strain, as depicted by the solid line in Fig. 1. Among them, point A is the stage of the damage initiation, and the path denotes the stage of the damage evolution. The dotted line denotes the stress strain behavior with no material damage. Furthermore, the calculation results of the material damage are closely related to the mesh size in the finite element model. To minimize the dependence of the calculated results on the mesh size, the damage evolution is defined as a function of plastic displacement or breaking energy. The damage factor is 0 before the material damage starts and 1 when the element fractures. Then, the element loses its bearing capacity, and the transmission tower rapidly enters the collapsing stage.

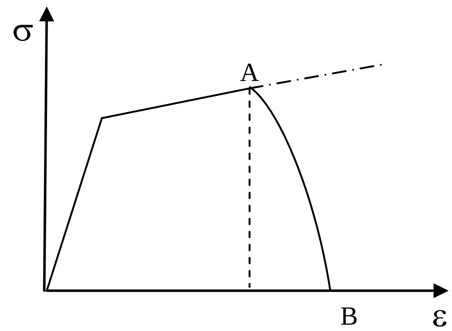


Fig. 1 – Stress-strain curve

3. Structural model and seismic wave

3.1 Finite element model of the transmission tower

A three-dimensional finite element model is created based on a section of a 500 kV transmission line in northeast China. A practical graph of the tower is depicted in Fig. 2. As indicated, the test tower consists of three cross-arms, and the maximum and minimum arm lengths are 10.45 m and 8 m, respectively. Based on the engineering data, the transmission tower is made of steel angles with a height of 53.9 m, and the tower size is illustrated in Fig. 3. The finite element model is depicted in Fig. 4. The primary members of the tower are made of Q345 steel with a 345 MPa yield stress, and the secondary members are made of Q235 steel with a 235 MPa yield stress, for which the elastic modulus is 206 GPa. The transmission towers are modeled using B31 beam elements. The base nodes of each transmission tower are fixed at the ground. An exponential form of the plastic displacement is used to define the damage evolution, which is suitable for steel.

Fig. 2 – Practical graph of the transmission tower

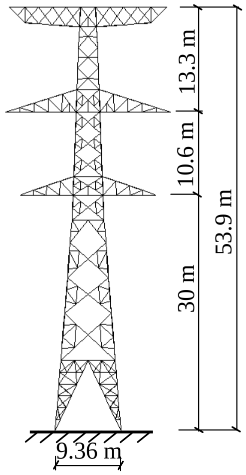


Fig. 3 – Elevation of the transmission tower

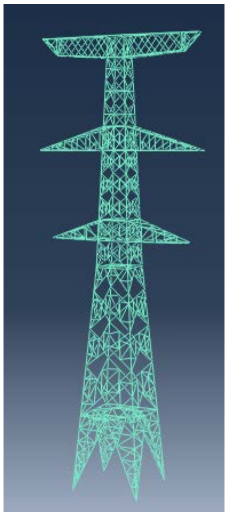


Fig. 4 –Finite element model of the transmission tower

3.2 Selection of the seismic waves

The selection of the seismic waves is a precondition for the time history analysis of the transmission tower. Considering the randomness of the ground motion and typicality of the load, three natural seismic waves (El Centro wave, Northridge wave and Taft wave) are selected, as listed in Table 1, and a dynamic time history analysis of the transmission tower is performed. Assuming that a larger peak acceleration of the seismic wave results in more significant damage, the amplitudes of the seismic waves are adjusted before the loads are inputted, and the peak acceleration after the adjustment is 20 m/s2. The seismic waves are inputted along the longitudinal direction.

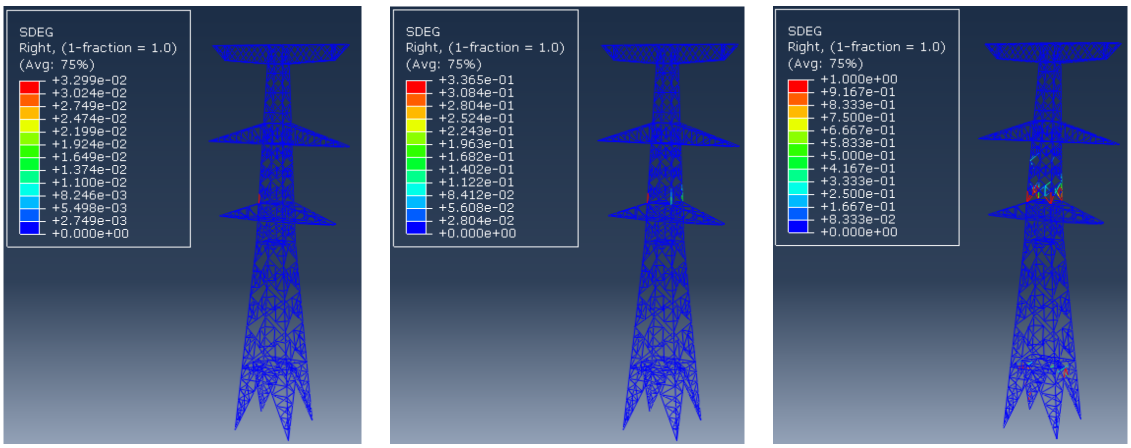
Table 1 – Seismic wave records

Number	Earthquake	Event date	Magnitude	Station
①	Imperial Valley	May 18, 1940	6.9	El Centro
②	Northridge	Jan. 17, 1994	6.6	La-Baldwin Hills
③	Kern County	Jul. 21, 1952	7.4	Taft

4. Analysis and discussion

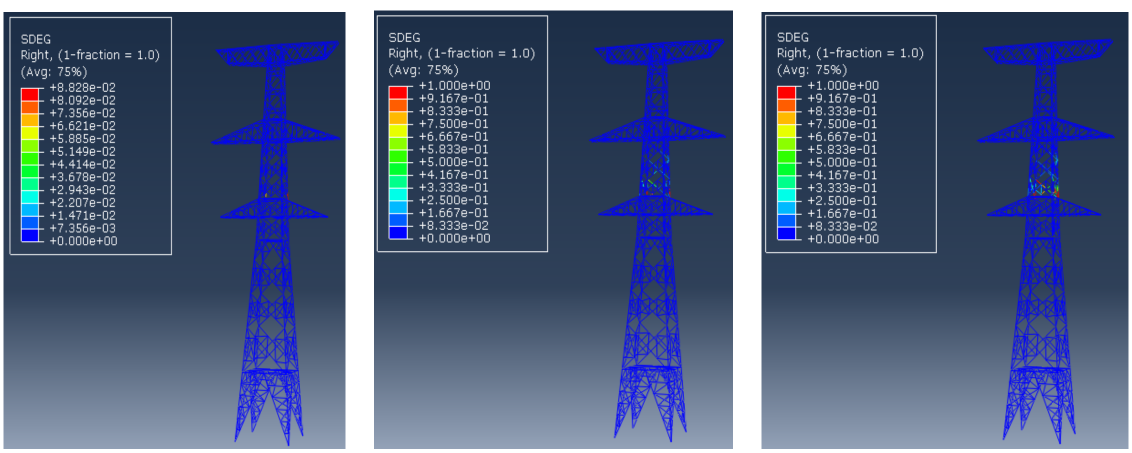
Considering the cumulative damage effect, a dynamic analysis of the transmission tower under the seismic waves selected above is performed. To study the effects of the material damage on the dynamic response of the transmission towers, the analysis results are compared with those without the damage effect.

The damage evolution of the tower under the El Centro seismic wave is depicted in Fig. 5. As indicated, the tower withstood the load well, and no damage occurred in any elements during the first 4.9 s. Then, at 4.92 s, an element in the main leg at a height of 32 m first reached the stage of damage initiation. With the continuous accumulation of damage, the damage factor depicted in Fig. 5 (c) reached 1, and several elements at a height of 32 m lost their load-bearing capacity.



(a) Time=5.08s (b) Time=5.12s (c) Time=6.2s

Fig. 5 – Damage evolution of the tower under El Centro seismic wave



(a) Time=22.50 s (b) Time=22.56 s (c) Time=22.62 s

Fig. 6 – Damage evolution of the tower under Northridge seismic wave

Fig. 6 illustrates the damage evolution of the tower under the Northridge seismic wave. It can be seen from the Fig. that the material damage started to accumulate at 5.08 s. At 6.20 s, the damage factors of a few elements at a height of 32 m reached 1, and the structure began to collapse.

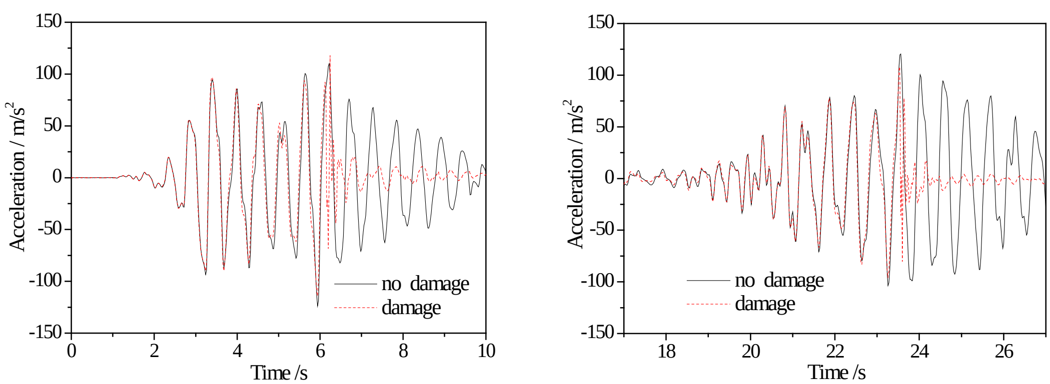
The acceleration time history curves at the top of the tower under the El Centro seismic wave and the Northridge seismic wave are illustrated in Fig. 7. It can be seen from the Fig. that the differences between the responses of the transmission tower with and without considering the material damage are clear. As indicated in Fig. 7 (a), the two-time history curves of the tower under the El Centro seismic wave are almost coincident in the beginning period of the seismic action. Starting from 4.92 s, differences began to appear, and the transmission tower-line system starts to collapse at 6 s. As indicated in Fig. 7 (b), the change laws of the time history under the Northridge seismic wave are the same as that under the El Centro seismic wave. The difference is the time when the tower enters the stage of damage evolution. The peak acceleration at the top of the tower under the Northridge wave considering the material damage effect is 10% lower than that without the material damage, and the tower starts to collapse at 23 s.

Additionally, the position of damage initiation and evolution of the transmission tower subjected to the El Centro seismic wave and the Northridge seismic wave are both approximately at a height of 32 m, which is where the tower eventually collapses. This result indicates that this position is a weak region of the tower and more prone to be affected by damage accumulation.

The damage evolution of the tower under the Taft seismic wave is illustrated in Fig. 8. As indicated, the damage factor started to change at 6.84 s at a position of 32 m in height. At 7.12 s, an element at a height of 40 m entered into the stage of damage evolution. As the damage accumulation progressed, although the value of the damage factor became larger, the element did not reach the assigned failure state.

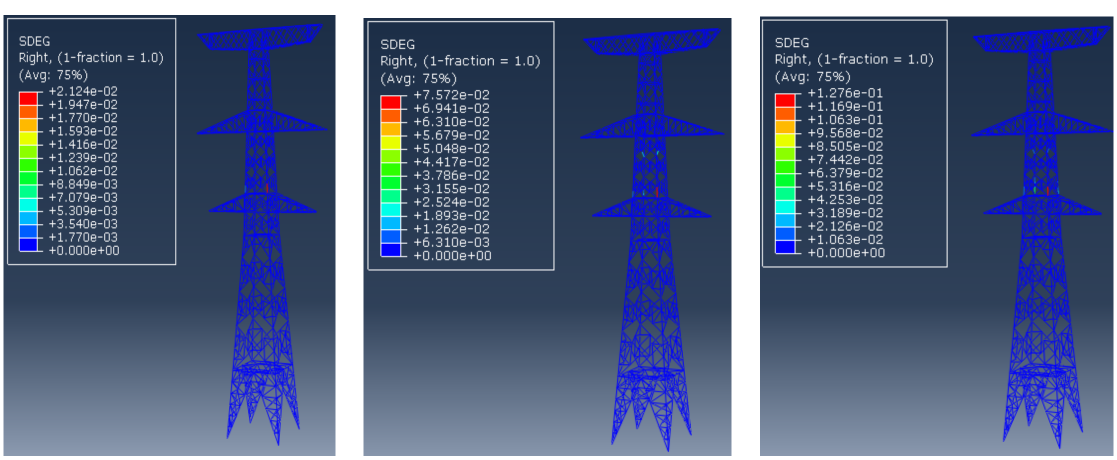
Fig. 9 depicts the acceleration time history curves at the top of the tower under the Taft seismic wave. It can be seen from the Fig. that the differences between the responses of the transmission tower with and without considering the material damage are more apparent compared to the other two seismic waves.

The analysis results indicate that the damage processes of the transmission tower are different under different seismic excitations; however, the initial fracture position occurs at approximately the same height, i.e., between 32 m and 40 m. This result should be considered in future designs.



(a) El Centro seismic wave (b) Northridge seismic wave

Fig. 7 – Comparison of acceleration time history curves at the top of the tower



(a) Time=6.86 s (b) Time=7.12 s (c) Time=22 s

Fig. 8 – Damage evolution of the tower under Taft seismic wave

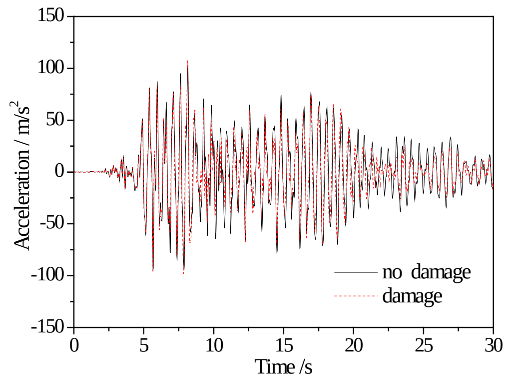


Fig. 9 – Comparison of acceleration time history curves at the top of the tower under Taft seismic wave

5. Conclusions

A three-dimensional finite element model of a transmission tower is established using ABAQUS. The dynamic response of the transmission tower considering damage accumulation effects under earthquake excitations is studied using a time history analysis. Based on the numerical analysis results, the following conclusions can be drawn:

(1) The structural response of the transmission tower considering the damage accumulation effect is different from that not considering the material damage effect.

(2) The differences between the responses of the transmission tower with and without considering the material damage are clear, and it is necessary to consider the material damage in the seismic design of transmission towers.

(3) The damage processes of the transmission tower are different under different seismic excitations; however, the initial fracture position occurs at approximately the same height, i.e., between 32 m and 40 m. This analysis result could be used as a reference basis for the safety assessment and structural design of transmission towers.

6. References

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