

Effect of elevated temperature on critical load in stability tests of the steel plate

Yu.P. Alexandrova^{1*}, *E.V. Suvorova*¹

¹Moscow Aviation Institute (National Research University), Volokolamskoe shosse, 4, 125993, Moscow, Russia

Abstract. This paper presents the results of a study on the effect of epoxy-polyester based powder coatings on the critical strength of plate specimens made of rolled steel sheets. The results show that the model using planar elements gives more accurate results than the model using three-dimensional elements. The best agreement with experiment was obtained with Ansys results using Eigenvalue bucling, less than 1%. The lowest experimental agreement was with the results obtained in Ansys using solid elements, about 70%.

1 Introduction

Preliminary experiments have shown that when studying the mechanical properties of metal plate specimens and polymer-coated metal plate specimens in stability tests, the elevated temperature affects only the coated specimens [1-17]. Therefore, the aim of this work was to perform numerical and analytical calculations of the stability of coated metal plate specimens [18-25]. The analytical calculation was performed for the samples at room temperature using the Euler formula. Numerical calculations were performed in Ansys software for batches of samples at room and elevated temperature.

2 Experimental studies on coating samples

Samples of rolled steel sheets with a constant thickness of 0.7 mm and, depending on the batch, different lengths and widths without and with coating were considered [26-43]. A EUROPOLVERI epoxy-polyester powder coating (RAL 9010, Italy) with a thickness of approximately 250 μm with a ± 30 μm spread was applied electrostatically. Before coating, the steel surface was degreased and phosphatised. The coating was carried out in a painting booth made by Gema (Switzerland). Drying was carried out at a temperature of 120 °C for not more than 5 minutes. Polymerization of the sprayed layer was carried out in a thermal chamber at 150°C for 30 minutes. The samples were cooled in air for several hours.

The working length of the 240 mm samples was 131.85 mm and the 120 mm samples was 86.15 mm. For the calculations, the length of the working zone was assumed to be 132 mm and 86 mm respectively. The specimens were tested at a constant speed of 0.5 mm/min.

* Corresponding author: gxtl@mail.ru

Mechanical grips were used on all specimens. When tested at elevated temperature, the specimen was held for 10 minutes.

It was anticipated that during the heating process, the coated specimen would loosen in the grips due to the softening of the coating and the need for an additional force to hold the specimen in place. To confirm this, the effect of an additional tightening of the mechanical grips was investigated during the resistance test for elevated temperatures. The only difference between the retracted and non-tightened tests was the additional retraction of the specimen after 5 minutes at 80°C. After retightening, the sample was held at the same temperature for an additional 5 minutes. Samples without retightening were held at 80°C for 10 minutes. For this study, 6 samples in each batch were considered:

Uncoated batch with sample size 240*24*0.9

Coated batch and sample size 240*24*1

Coated batch with sample size 120*24*0.9

Coated batch and sample size 120*24*1

This study showed the need for additional tightening of the coated samples. Therefore, all the remaining coated samples were retightened after 5 minutes at 80 °C.

In order to study the effect of the coating on the critical force in the elevated temperature test, 12 batches were considered. Each batch contained 5 specimens and each specimen was held at 80°C for 10 minutes. The coated batches were further tightened. The following batches were tested:

Uncoated batch with sample size 240*24*0.7

Coated batch and sample size 240*24*1.2

Coated batch with specimen size 120*24*0.7

Coated batch with sample size 120*24*1.2

Coated batch with 120*12*0.7 sample size

Coated batch and 120*12*1.2 specimen size

Mechanical tests were performed on an Instron 5969 (UK) with Bluehill 3 software. Standard Ansys finite element analysis techniques were used for numerical simulation of the stability loss tests.

3 Numerical modelling methods and results

The following values for the physical and mechanical properties of the samples were used in the calculations:

Sheet steel: Modulus of elasticity $E = 200 \text{ GPa}$, Poisson's ratio: $\mu = 0.3$, Thermal expansion coefficient: $\alpha = 12.5 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$, EUROPOLVERI coating: Modulus of elasticity: $E = 3 \text{ GPa}$, Poisson's ratio $\mu = 0.03$, Thermal expansion coefficient: $\alpha = 55 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$.

In the numerical calculations, the possible curvature of the sample was taken into account by specifying the initial curvature with a radius. The calculation for elevated temperature took into account polymerisation at temperature 150 °C taking the temperature change relative to the neutral state equal to -70 °C.

A curved surface with a radius of curvature was constructed in Ansys $1 \cdot 10^7 \text{ mm}$. Two simulations of the experimental samples were considered: two-dimensional simulation: the surface was partitioned with two-dimensional QUAD elements; and three-dimensional simulation: the solid was partitioned with three-dimensional Hex elements. To simulate a fixture similar to the experiment, boundary conditions were set: The bottom face was given embedding conditions (prohibiting movements and rotations in all directions). The upper face was conditioned to forbid displacement in the direction of width Oh and thickness Oz of the specimen, and rotation around the direction of specimen width Rx . The load was set on the upper face in the Oy axis as a force. The coating was modeled by a layered section function.

The value of critical force is determined from the formula of the theory of stability of rods for the case of vertical action of the load and a rigid pinch at the ends of the rod:

$$P_{cur} = \frac{4 \pi^2 EJ}{l^2}$$

here $l = 86 \text{ mm}$ is stem length, E defines Young's modulus, J is the moment of inertia of the rod cross section.

When modelling uncoated plates, we assume: $E = E_{st}$ – Young's modulus of steel, $J = J_{st} = bh^3/12$ – moment of inertia of specimens of thickness h and width b . When modelling coated plates, the bending stiffness of the respective rod must be calculated taking into account the additional contribution from the coating layers: $EJ = 2E_c J_c + E_{st} J_{st}$, where E_n is the coating modulus of elasticity, J_c – the moment of inertia of the coating layers displaced relative to the neutral line of the rod. However, the use of such a refined estimate leads to a small change in the calculated critical load (within 2%), which cannot explain the experimental data obtained. Therefore, a single value of the critical load calculated without the influence of the coatings is shown in the graphs.

The dependence of the specimen curvature on the critical load is shown in Figure 1.

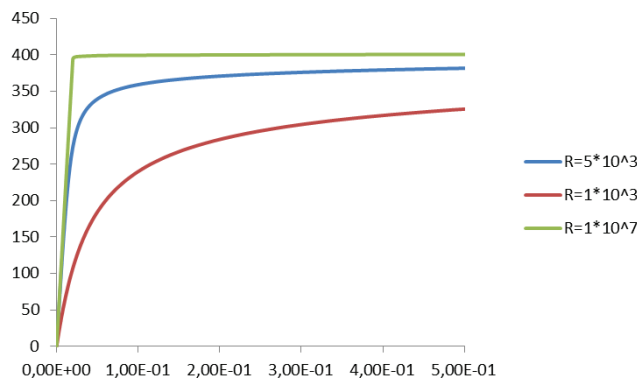


Fig. 1. Dependence of critical load on given sample curvature for sample size 120*12 mm.

The effect of the coating thickness on the critical strength of the sample is shown in Fig. 3.

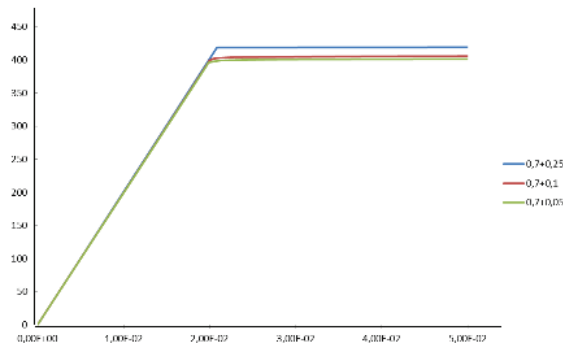


Fig. 2. Effect of coating thickness for samples 120*12.

The difference between the results obtained numerically and the experiments was justified, namely the slope angle of the load-displacement curve. The figure below shows the experimental results and the numerical results using planar and three-dimensional elements.

An analytical relationship was obtained to verify the numerical calculations:

$$U = \frac{P}{S_x E} L,$$

where U is displacement, P is load, L is the length of the working part, E is the modulus of elasticity, S_x the sample area. Shown in green in the graph.

The results for the coated samples are given in Figure 3 and 4.

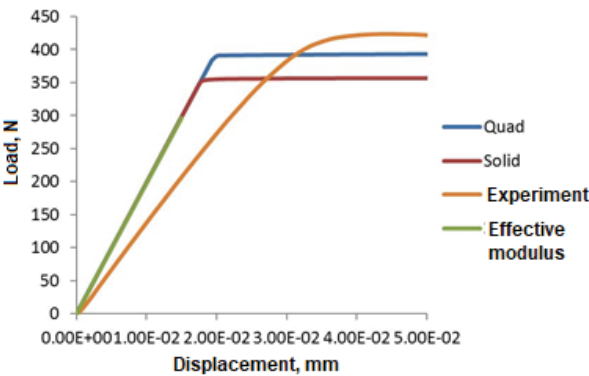


Fig. 3. Experiment results.

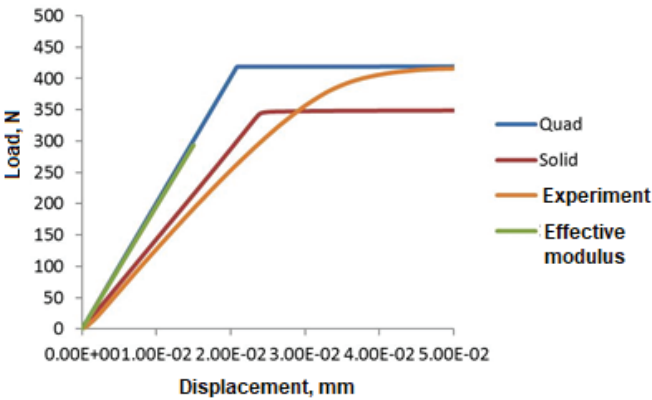


Fig. 4. Results of the numerical experiment.

Figure 4 shows that the slope value obtained analytically coincides with the results obtained numerically using planar elements. The results obtained using three dimensional elements are significantly different. This may be due to the accumulation of error.

This result shows that the plane element model gives more accurate results than the three dimensional model.

The best fit with experiment is the one obtained in Ansys using Eigenvalue bucling, less than 1%. The lowest agreement with experiment was obtained in Ansys using Solid Elements, about 70%.

4 Conclusions

The numerical results obtained for different moduli showed that the deviation of the numerical curve from the experimental curve is not due to the physical and mechanical properties and geometrical characteristics of the sample but to the results obtained. Since the change in displacement at the end of the specimen was measured along the cross-head, the slope of the curve in this situation may not be true and may not coincide with the slope obtained numerically. It should also be taken into account that the loading rate of the sample was 2 times lower than the loading rate for determining the modulus of elasticity.

References

1. V.F. Formalev, S.A. Kolesnik, B.A. Garibyan, Herald of the Bauman Moscow State Technical University, Series Natural Sciences **(1)**, 107–121 (2022)
2. V.F. Formalev, B.A. Garibyan, S.A. Kolesnik, Herald of the Bauman Moscow State Technical University, Series Natural Sciences **(4)**, 80–94 (2022)
3. S. Radaev, International Journal of Mechanics **15**, 196–203 (2021)
4. V.F. Formalev, S.A. Kolesnik, B.A. Garibyan, Herald of the Bauman Moscow State Technical University, Series Natural Sciences **(92)**, 44–59 (2020)
5. A.S. Zinchenko, Asia Life Sciences Suppl. **22(2)**, 243–256 (2020)
6. A.N. Astapov, V.A. Pogodin Russian Metallurgy (Metally) **12**, 1529–1533 (2021)
7. S. Radaev, International Journal of Mechanics **15**, 172–180 (2021)
8. N.A. Bulychev, L.N. Rabinskiy, O.V. Tushavina, An Int. J. **11**, 1, 15–21 (2020)
9. S. Radaev, WSEAS Transactions on Appl. and Theoretical Mech. **16**, 142–149 (2021)
10. N.A. Bulychev, S.A. Kolesnik, IOP Conf. Proceedings **2231**, 012012 (2022)
11. N.A. Bulychev, Nanoscience and Technology: An International Journal **13**, 1, 55–65 (2022)
12. S.A. Kolesnik, AIP Conf. Proceedings **2402**, 020026 (2021)
13. M.O. Kaptakov, Int. J. of Pharmaceutical Research **12**, 2, 1821–1824 (2020)
14. O.A. Butusova, Int. J. of Pharmaceutical Research **12**, 4, 2292–2296 (2020)
15. A.N. Tarasova, Int. J. of Pharmaceutical Research **12**, 2, 1160–1168 (2020)
16. O.A. Butusova, Int. J. of Pharmaceutical Research **12**, 2, 1147–1151 (2020)
17. N.A. Bulychev, Int. J. of Hydrogen Energy **47**, 50, 21323–21328 (2022)
18. N.A. Bulychev, A.Yu. Burova, Int. J. of Hydrogen Energy **47**, 63, 26789–26797 (2022)
19. N.A. Bulychev, Int. J. of Hydrogen Energy **47**, 84, 35581–35587 (2022)
20. O.A. Butusova, Int. J. of Pharmaceutical Research **12**, 2, 1152–1155 (2020)
21. A.V. Perchenok, E.V. Suvorova, A.A. Farmakovskaya, V. Kohlert, Int. J. of Circuits, Systems and Signal Processing **15**, 1414–1420 (2021)
22. O.A. Butusova, International J. of Pharmaceutical Res. **12**, 2, 1156–1159 (2020)
23. A.N. Tarasova, Int. J. of Pharmaceutical Research **12**, 2, 1173–1180 (2020)
24. M.O. Kaptakov, Int. J. of Pharmaceutical Res. **12**, 2, 1838–1843 (2020)
25. A.N. Tarasova, International J. of Pharmaceutical Res. **12**, 2, 1169–1172 (2020)
26. M.O. Kaptakov, Int. J. of Pharmaceutical Res. **12**, 2, 1851–1855 (2020)
27. Yu.V. Ioni, O.A. Butusova, AIP Conference Proc. **2402**, 020035 (2021)

28. A.Yu. Burova, J. of Physics: Conf. Series **2308(1)**, 012006 (2022)
29. Yu.V. Ioni, O.A. Butusova, AIP Conference Proceedings **2402**, 020036 (2021)
30. A.Yu. Burova, Journal of Physics: Conf. Ser. **2096(1)**, 012060 (2021)
31. A. Burova, A. Ryapukhin, AIP Conf. Proceedings **2402**, 040002 (2021)
32. A.Y. Burova, J. of Physics: Conf. Series **1889(2)**, 022003 (2021)
33. V. Goncharenko, Yu. Mikhaylov, N. Kartushina, Neural Computing and Applications **34**, 5, 4033-4045 (2022)
34. A.V. Perchenok, E.V. Suvorova, A.A. Farmakovskaya, V. Kohlert, WSEAS Transactions on Applied and Theoretical Mechanics **16**, 127-133 (2021)
35. S.A. Kolesnik, N.A. Bulychev, Journal of Physics: Conf. Ser. **1474**, 012024 (2020)
36. B.A. Garibyan, Int. J. of Pharmaceutical Res. **12**, 2, 1825-1828 (2020)
37. N.A. Bulychev, Nanoscience and Technology: An International Journal **12**, 3, 91-97 (2021)
38. N.A. Bulychev, High Temperature **60**, 1, S98–S126 (2022)
39. G.A. Kalugina, A.V. Ryapukhin, Russian Eng. Res. **41**, 7, 627-630 (2021)
40. M.O. Kaptakov, AIP Conf. Proceedings **2402**, 020027 (2021)
41. B.A. Garibyan, Int. J. of Pharmaceutical Res. **12**, 2, 1829-1832 (2020)
42. S.A. Kolesnik, AIP Conf. Proceedings **2402**, 020037 (2021)
43. M.O. Kaptakov, E.A. Pegachkova, A.V. Makarenko, AIP Conf. Proc. **2402**, 020038 (2021)