**Demiryolu Mühendisliği** **Railway Engineering**
Temmuz 2023 July 2023
Sayı:18, Sayfa: 98-108 Issue:18, Page: 98-108
Araştırma Makalesi Research Article
doi: 10.47072/demiryolu.1295172
http://dergipark.org.tr/demiryolu
e-ISSN: 2687-2463, ISSN: 2149-1607

# Investigation of Contact Force and Stress Relationship in Overhead Line Contact Wires with Finite Element Method

Özgün SUNAR

*Eskisehir Technical University, Transportation Vocational School, Eskisehir, Turkey*

*ozgunsunar@eskisehir.edu.tr*

*(Alınış/Received: 10.05.2023, Kabul/Accepted: 31.05.2023, Yayımlama/Published: 31.07.2023)*

**Abstract:** Railway overhead line electrification (OLE) is used for providing continuous power to the trains throughout catenary wires and the current collector device of the pantograph. The interaction of contact force exerted by the pantograph and contact wire is an important topic in regulating OLE dynamics. OLE components are subjected to fluctuating contact forces due to the trains running with high speed, therefore, it is important to estimate service life of contact wires and pantograph carbon collectors by considering contact wire/pantograph interference. This study performs a number of contact force and stress/strain analysis of standard OLE designs used in Europe, Series 1, Sicat S1.0, Sicat H1.0, Re250 and EAC 350, with finite element method. The results establish a link between stress levels and contact force in the contact lines depending on the design parameters of contact wire type, pretension, span-length, and contact wire material. Understanding the bending of the contact wire due to the contact force will help to predict potential failures in mainlines and extend our knowledge of safety and reliability of various OLE design parameters.

***Keywords**:* Contact wire, Finite element analysis, Stress, Contact force, Overhead line equipment

## Demiryolu Havai Hatlarında Pantograf Kuvveti ve Seyir Teli Gerilimi İlişkisinin Sonlu Elemanlar Yöntemi ile İncelenmesi

**Öz:** Demiryolu havai hat elektrifikasyonu pantograf cihazı ile katener hatlara sürekli olarak enerji sağlamaktadır. Pantograf ve seyir teli etkileşimi, havai hat dinamiklerinin incelenmesinde önemli bir rol oynamaktadır. Havai hat bileşenleri yüksek hızda seyreden trenler nedeniyle dalgalı temas kuvvetlerine maruz kalırlar. Bu sebeple kontak teli/pantograf etkileşimi kontak tellerinin ve pantograf karbon çubuklarının çalışma ömrünün tahmin edilmesinde önem arzetmektedir. Bu çalışma, Avrupa'da kullanılan bir dizi standart havai hat tasarımında, Series 1, Sicat S1.0, Sicat H1.0, Re250 ve EAC 350, temas kuvveti ve seyir teli gerilim/gerinim ilişkisini sonlu elemanlar yöntemiyle incelemektedir. Elde edilen sonuçlar ön gerilim, hat uzunluğu, temas teli malzemesinin çeşidi ve gerilim-temas kuvveti arasında bir ilişki kurmaktadır. Pantograf temas kuvvetinin seyir telinde oluşturduğu eğilme etkisini anlamak, ana hatlardaki potansiyel arızaların önceden tahmin edilmesine katkıda bulunacak ve çeşitli havai hat tasarım parametrelerinin güvenilirliğinin belirlenmesinde önemli bir rol oynayacaktır.

***Anahtar kelimeler**:* Seyir teli, Sonlu elemanlar analizi, Gerilme, Temas kuvveti, Katener hatlar

## 1. Introduction

Overhead line equipment (OLE) is designed for providing constant electrical power to trains throughout physical and electrical contact of on-roof equipment pantograph and the contact wire. In order to maintain the contact wire and pantograph collector surfaces in contact, the pantograph exerts a contact force to the contact wire in upward direction and droppers hold the messenger wire and contact wire together and in position (Figure 1). OLE wires work under various factors such as; high voltage, pretension, contact force and wear. Since any failure in OLE lines may lead to catastrophic incidents, durability and the reliability of OLE designs are vital in electric trains operation.

Atıf için/Cite as: Ö. Sunar, "investigation of contact force and stress relationship in overhead line contact wires with finite element method," *Railway Engineering*, no. 18, pp. 98-108, July 2023, doi: 10.47072/demiryolu.1295172

Speaking about the dynamics of the contact wire during trains operation, a static uplifting contact force, which is at least 60 N depending upon the configuration of the overhead line system and type of pantograph is applied to the contact wire by the pantograph to sustain a continuous current flow from OLE to the pantograph [1]. The contact force interaction problems can be shown one of the most significant issues that needs to be considered and may result in mechanical failure of the contact wire. Although models in standards (BS EN 50317, BS EN 50318 and EN 50367) restricts standard contact force up to 230N at 300 km/h [2-4], due to the contact wire profiles and OLE fitting structures (section insulators, neutral sections, clamps), higher contact forces can be experienced during the journey of trains. This contact force generates elevated bending stress in the contact wire.

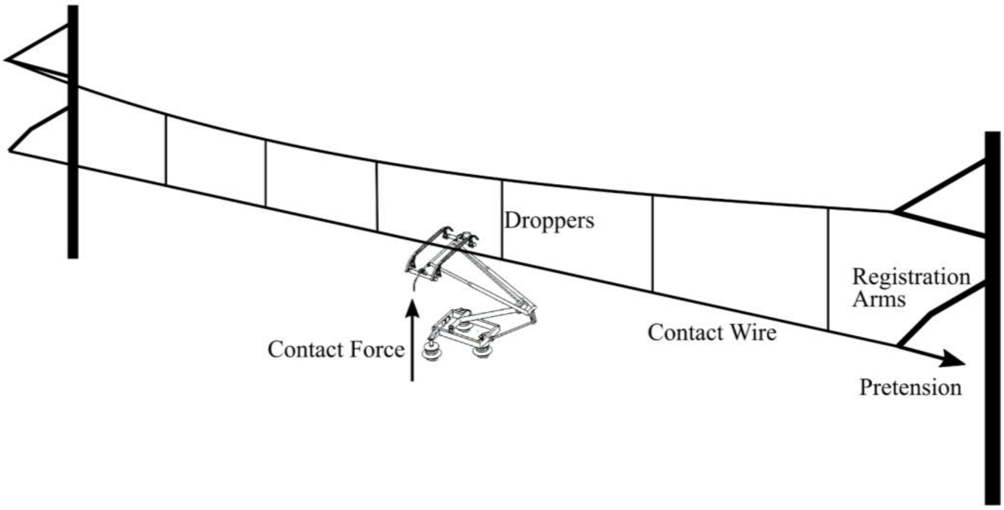

**Figure 1**. Features of overhead line components

Contact wires are often replaced between 30-50 years due to the sliding wear problem [5] However recent studies have showed that the wear is not the mere life limiting factor, other factors such as; fatigue, electrical discharge or OLE dynamics could be prior to wear failure [6]–[10]. A number of studies in the literature investigated pantograph and contact wire interactions with experimental and numerical methods.

Regarding the contact force and train speed relation, Wenxuan et al. [11] found that uplift amount of the contact wire is positively related to the speed of trains, particularly over speed of 300 km/h. In the same vein, Gregori et al. [12] indicated that current collection quality becomes limiting when increasing the speed of railway systems. Looking at the details of the pantograph contact wire interaction, Kim et al. [13] directly linked the uplift displacement and the bending strain of the contact wire and concluded that the contact force could be the most important factor in determining the systems fatigue life.

Particularly, determining the stress levels in the contact wire due the pantograph uplift is an essential criterion for the reliability of the OLE systems. A number of experimental procedures exist in the literature. Most of the research used 2-3 metre-length experimental configurations to assess life value of contact wires under dynamic loading. In almost all the test configurations are used three point bending configurations [14]–[16].

Taken together, these studies indicate that the contact force-contact wire interaction plays a critical role in determining service life OLE systems. This study investigates various existing OLE designs and provides new insights into contact force-stress relations with finite element analysis. The result of this study makes a major contribution to research on OLE safety and reliability and understanding stress levels that could occur on the contact wire geometry due to the varying contact forces.

## 2. Background

A variety of different overhead contact line designs have been used in the world. Although the equipment shows similarities, span lengths, contact wire types, pretension and stitch wire connections differ between these designs. Before establishing finite element models for the properties of various designs used in Europe, Series 1, Sicat S1.0, Sicat H1.0, Re250 and EAC 350 were reviewed, and span stiffness profiles were explained in this section.

Series 1 (140 mph ≈ 225 km/h) , EAC 350 (350 km/h), Sicat S1.0 (230 km/h), Sicat H1.0 (350 km/h) and Re250 (250 km/h) are very common designs used in Europe. Series 1 differs from the other designs because no stitch wire exists. Some locations where the selected designs used are EAC350 (RENFE) from Madrid to French border through Barcelona, Spain, Sicat H1.0 and Sicat S1.0 (Siemens) in Cologne-Rhine main line and Cologne-Bonn, respectively [17], [18], Re250 (German DB design) in Lotschberg base tunnel, Switzerland and Series 1 in Great Western Electrification (United Kingdom) [19]. Table 1 shows the technical properties of selected OLE designs.

It has been known that the parameters of pretension, contact wire type, span lengths and stitch wires were the critical elements in OLE dynamics. The geometry and properties of OLE designs are shown schematically in Figure 2. The contact wire deformation under contact force varies in a span-length distance due to the different design parameters. Figure 3 contact wire stiffness profiles across a span-length [20].

**Table 1**. Properties of different OLE designs

| Design Name | Parameters | | | | |
|---|---|---|---|---|---|
| | Pretension (kN) | Span Length (m) | Mid Span Stiffness (N/mm) | Contact Wire | |
| | | | | Type | Material |
| Sicat S1.0 | 12 | 80 | 0.90 | AC-100 | CuAg |
| Sicat H1.0 | 27 | 70 | 2.38 | AC-120 | CuMg |
| Re 250 | 15 | 65 | 1.81 | AC-120 | CuAg |
| EAC 350 | 31.5 | 64 | 2.81 | AC-150 | CuMg |
| Series 1 | 16.5 | 65 | 1.85 | AC-120 | CuAg |

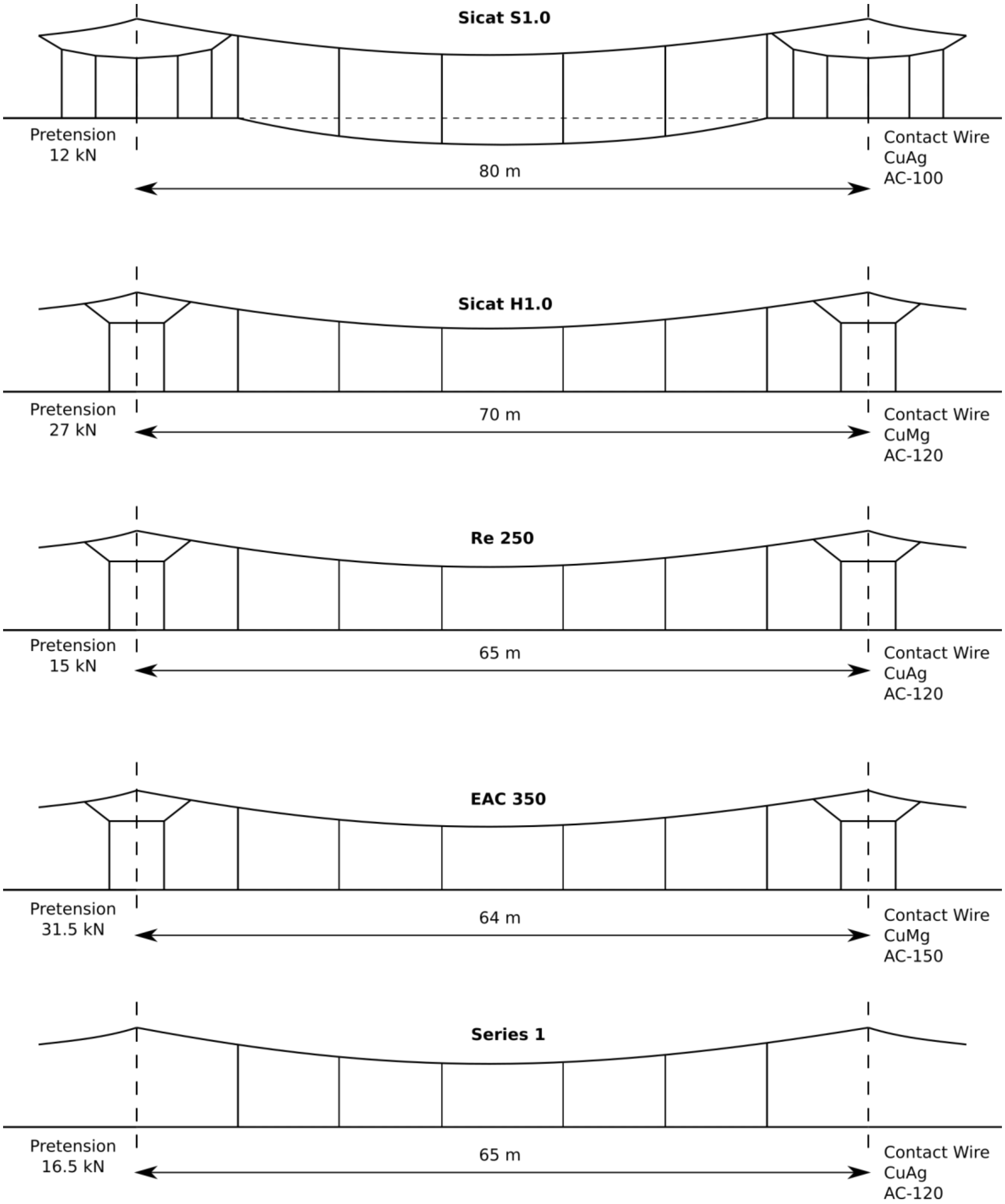

**Figure 2**. Geometric properties of standard series in UK and EU mainlines

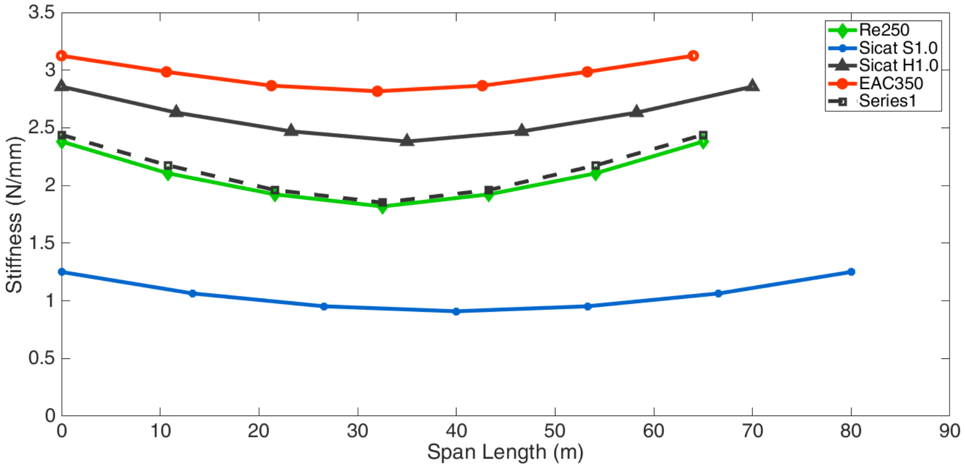

**Figure 3.** Stiffness properties along a span length

## 3. Methods

Individual FE models were developed based on the boundary conditions in a span length of the contact wire for selected OLE designs. The finite element models were designed in Ansys Workbench. Regarding boundary conditions, the contact wire was vertically and horizontally supported from the registration arms. The registration arms restrict vertical movement of the contact wire; however, they also have the flexibility to tolerate uplifting pantograph force. This vertical allowance was defined to the registration arms with spring connections, and a stiffness value was set by using the literature data explained in Section 2. For the lateral and rotational boundary conditions, the model was free to rotate around z-axis at the points of A and B. In order to give lateral movement flexibility (as simply supported beam), the point B was also free to move in x-axis. Figure 4 shows the boundary conditions of the FE model of the contact wire.

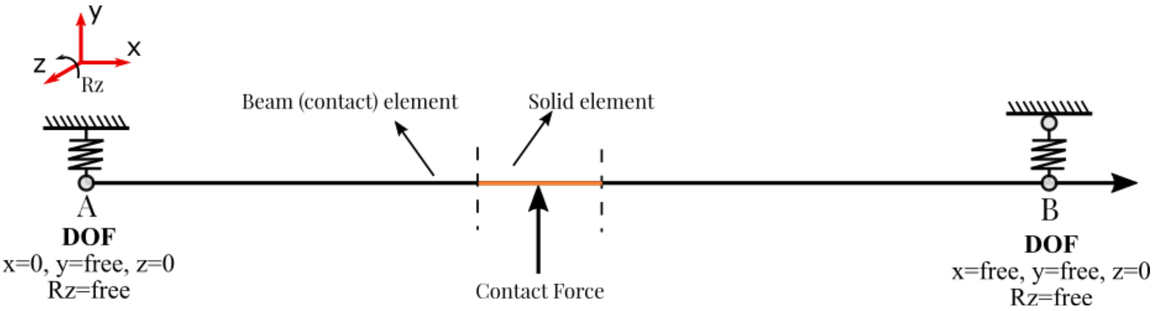

**Figure 4**. Schematic of boundary conditions of a span-length contact wire

Droppers are used to prevent sagging and keep the contact wire in a flat position. Because the contact wire was subjected to uplifting, the droppers were not restricting the vertical movement. It was known that the droppers are essential for dynamic analysis of the contact wire; however, this was only a static model. Therefore, the dropper connections were not taken into consideration in the model. The uplifting force was applied from the middle of the spans, and the maximum stress was expected to be in the centre. In order to minimise the solving time, a-metre length of the contact wire was connected to the registration arm connections with beam(contact) elements.

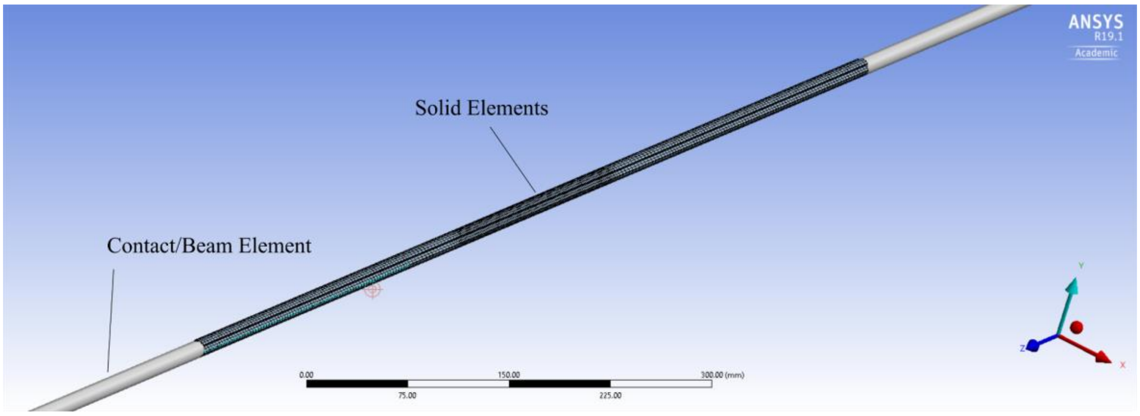

**Figure 5.** Finite element model with the mesh and beam connections

Figure 5 shows the finite element model developed to investigate the relationship between contact force and stress in the contact wire. The model was divided into three regions for meshing, namely; coarse, fine and very fine. Mesh sizing of the model was finer from the sides to the centre of mid-span since maximum stress was expecting here. A growth ratio of 1.2 was used between the regions. Table 2 shows the convergence analysis of the simplified model with mesh size, the number of elements, changes in strain and mesh quality. The % change in strain in each iteration was calculated related to the strain at the first iteration. Figure 6 also shows the change in mesh quality with an increasing number of elements. Mesh quality checks showed that the quality of the mesh became very stable at iteration number 9. Increasing the number of elements did not significantly contribute to the mesh quality from this point on. Therefore, the mesh size was set to be 1, 1.2 and 1.4 mm for the regions of very fine, fine and coarse, respectively. Reference tensile properties of copper silver and copper magnesium contact wire with the cross-section of 100 mm$^2$, 120 mm$^2$ and 150 mm$^2$ were used [13], [21], [22].

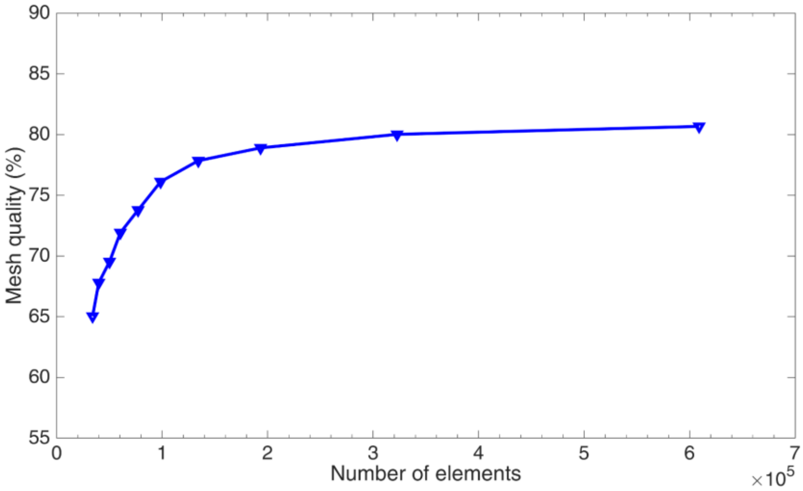

**Figure 6**. Convergence analysis results of the FE model

**Table 2**. Mesh parameters used in convergence analysis

| Iteration Number | Mesh Size (mm) | | | Number of Elements | Change in Strain (%) | Mesh Quality (%) |
|---|---|---|---|---|---|---|
| | Very Fine Zone | Fine Zone | Coarse Zone | | | |
| 1 | 3.00 | 3.6 | 4.32 | 609004 | - | 65.03 |
| 2 | 2.75 | 3.3 | 3.96 | 322691 | 2.22 | 67.80 |
| 3 | 2.50 | 3.0 | 3.60 | 193255 | 2.39 | 69.53 |
| 4 | 2.25 | 2.7 | 3.24 | 134261 | 3.58 | 71.92 |
| 5 | 2.00 | 2.4 | 2.88 | 98524 | 2.71 | 73.77 |
| 6 | 1.75 | 2.1 | 2.52 | 77145 | 5.71 | 76.11 |
| 7 | 1.50 | 1.8 | 2.16 | 60356 | 5.12 | 77.84 |
| 8 | 1.25 | 1.5 | 1.80 | 50117 | 8.26 | 78.90 |
| 9 | 1.00 | 1.2 | 1.44 | 39906 | 9.51 | 80.01 |
| 10 | 0.75 | 0.9 | 1.08 | 34019 | 9.36 | 80.66 |

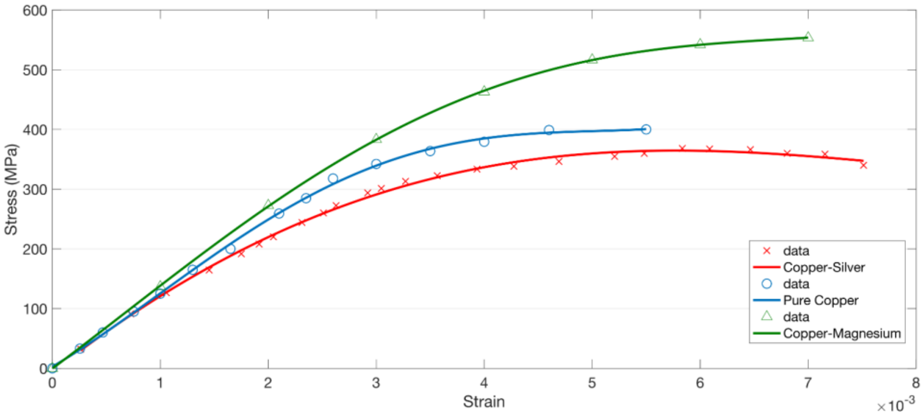

**Figure 7**. Tensile strength of CuAg, Pure Copper and CuMg contact wires

## 4. Results

In order to understand how different designs had behave under the pantograph contact force, the stress and strain changes of a span length contact wire with a range of contact force were investigated with FE method. Figure 8 shows the maximum stress in the middle span of OLE designs with an increasing contact force from 100N to 300N. Sicat H1.0 and EAC350 initially were subjected to higher stress than other three designs of Sicat S1.0, Re250 and Series 1 under 100 N contact force. The main reason for this was because Sicat H1.0 and EAC350 worked higher pretensions which were 27 kN and 31.5 kN, respectively. Further analysis of the relationship of the contact force and the maximum stress showed that maximum stress in all of the designs rose against increased contact force. However, the designs of Sicat H1.0 and EAC 350 were the ones that contained the two highest stress levels with just below 350 MPa and 300 MPa. The rest of the designs, Sicat S1.0, Re 250 and Series 1, showed very similar behaviour to one another and varied between just over 180 MPa to in the order of 250 MPa in the contact force range of 100-300 N.

In addition to the stress in the contact wire, the maximum strain was also analysed. The relationship between the contact force and contact wire strain is shown in Figure 9. The designs containing copper-magnesium grades of contact wire, Sicat H1.0 and EAC 350, were subjected to the highest strain. However, the most significant increase in the strain was seen in the designs containing copper silver grade contact wires, Sicat S1.0, Re250 and Series 1, as to be in the order of 50 %, while it was just over 20 % and 30 % for main lines of EAC350 and Sicat H1.0 which were equipped with copper-magnesium contact wire.

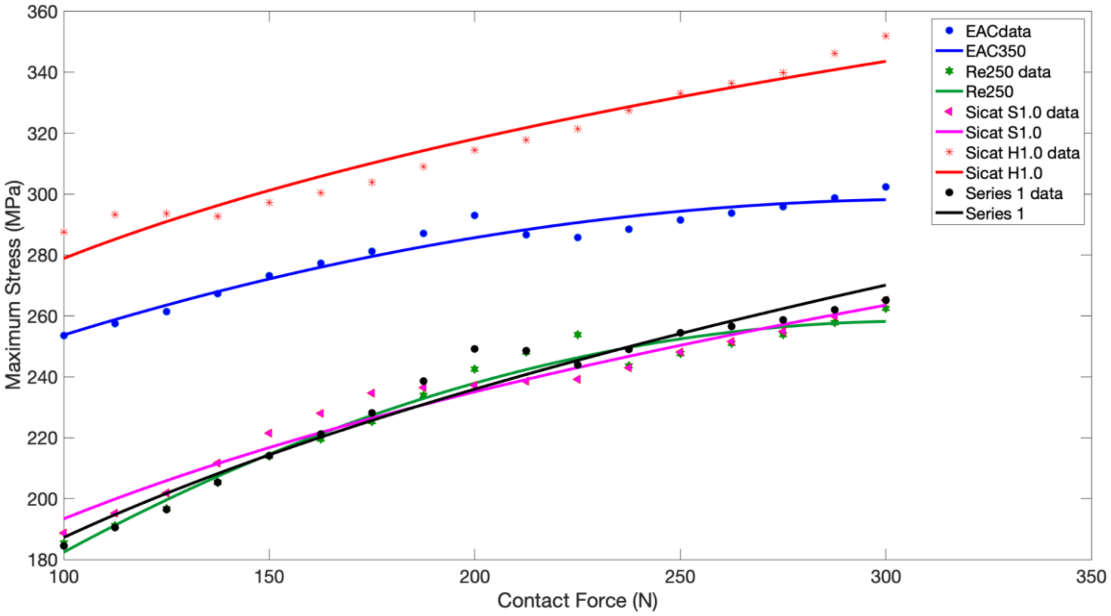

**Figure 8.** Relationship between contact force and maximum stress for different overhead line designs

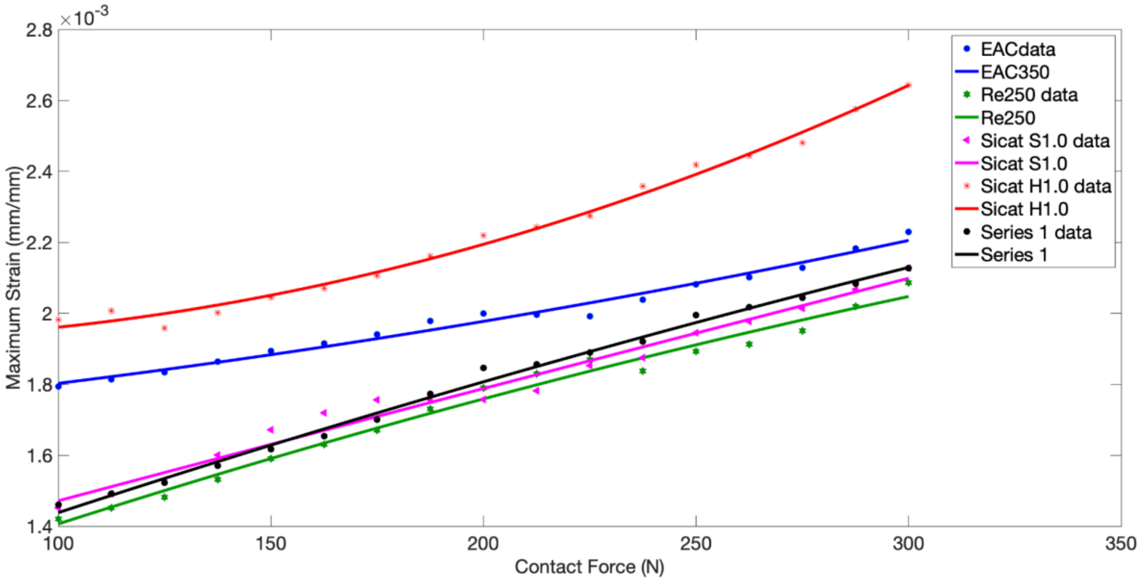

**Figure 9.** Relationship between contact force and maximum strain for different overhead line designs

Figure 10 presents the stress change in the contact wire section for selected OLE designs at maximum contact force of 300 N. The highest stress was observed on the top surface of the contact wire due to the bending effect of the contact force. Designs having the highest maximum stress at 300 N contact force are Sicat H1.0, EAC350, Series 1, Sicat S1.0, Re250, respectively.

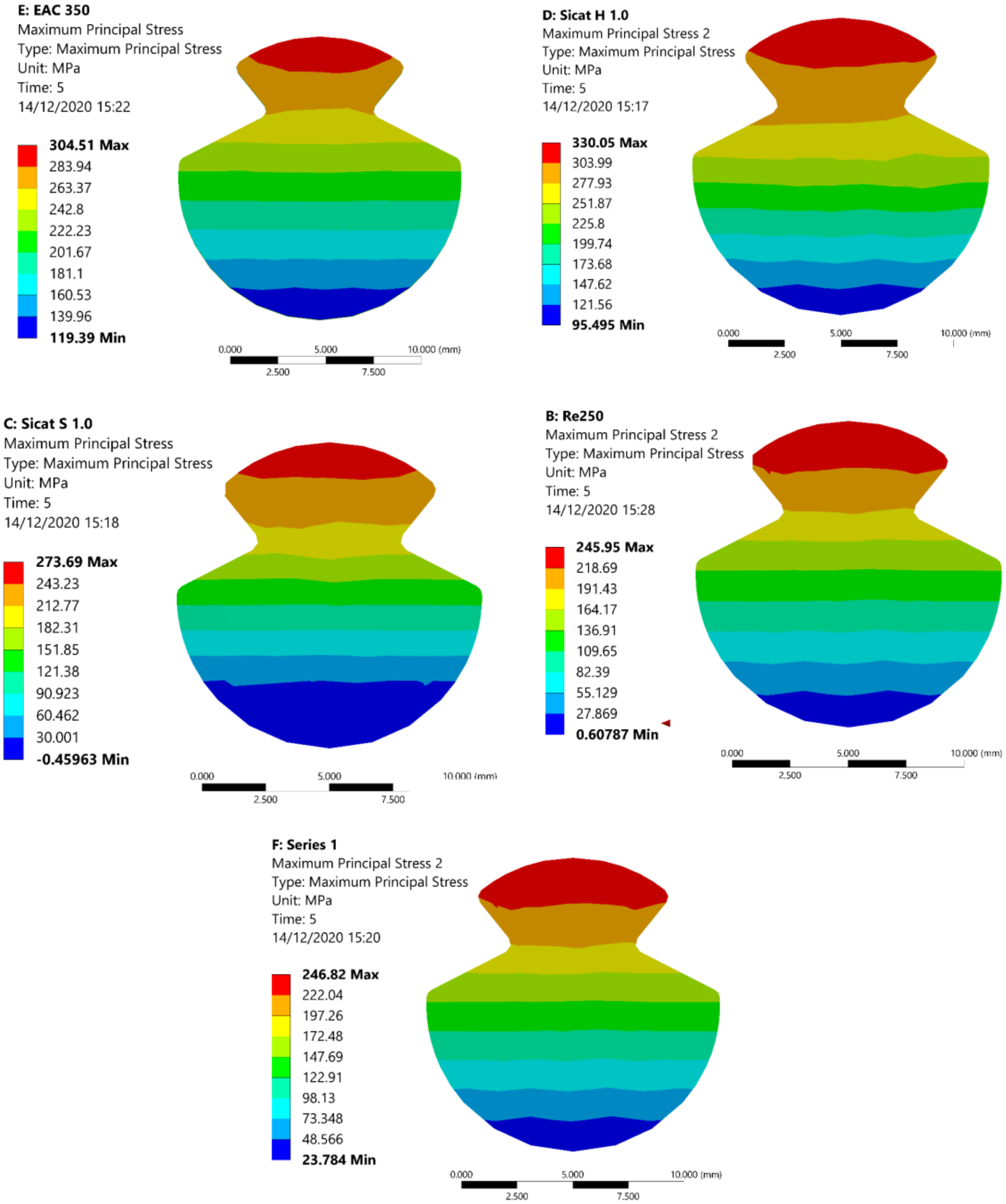

**Figure 10**. Stress distribution in the section of contact wire

## 5. Discussion

Results from analysis of real OLE contact wires completed with the contact force range between 100 N and 300 N showed that the maximum strain in the contact wire could reach at the very high end of the elastic limit of the material. The increase in the speed of trains over 300 km/h could even elevate the strain (and stress) to higher levels. This will eventually result in plastic deformation in OLE contact wires. It was apparent that copper-silver contact wires were subjected to severe stress compared to the others. One of the main reasons why the most significant increase was seen in the copper-silver based contact lines can be explained by lower Young’s modulus of copper-silver material rather than copper-magnesium grade. Because some level of plastic deformation is expected at high level contact forces (over 300 N), in life predictions and safety calculation, it would be more beneficial to use of strain-based calculation theories. Although reference model in BS EN 50138 [3] restricts maximum contact force between 190-210N at 250 km/h, some inspection data show that contact force can exceed this reference value and reach more than 300N [22]. Eventually, in long term high stress/strain amplitudes in the contact wire could turn this bending problem into a fatigue problem and under repetitive loading OLE cables can fail prior to its expected service life. Although the wear life is a primary criterion in determining the life cycle of the contact wire, large stress/strain levels show that with the increase of trains speed, fatigue problem may be more predominant in deciding the long-term service of OLE contact wire.

## 6. Conclusions

The present study set out to investigate contact force and contact wire stress relationship in OLE designs commonly used in European railways throughout finite element analysis. The findings of this research provide insights for stress levels in the contact lines depending on the design parameters of contact wire type, pretension, span-length, and contact wire material. This new understanding should help to improve predictions of failures in mainlines and extend our knowledge of safety and reliability of various OLE design parameters.

## Acknowledgement

Special thanks to Prof David Fletcher, Furrer + Frey and Network Rail, The University of Sheffield for their support to this research.

## References

[1] ‘EN 50206-1:2010 Railway applications - Rolling stock - Pantographs : Characteristics and tests - Part 1 : Pantographs for main line vehicles’. 2010.

[2] BSI, ‘BS EN 50317: Railway applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line’, p. 20, 2012.

[3] BSI, ‘BS EN 50318 : Railway applications - Current collection systems - Validation of simulation of the dynamic interaction between pantograph and overhead contact line’, vol. 3, p. 20, 2012.

[4] BS EN 50367-Railway applications - Current collection systems - Technical criteria for the interaction between pantograph and overhead line

[5] J. W., S. Longhurst, and C. A. Brebbia, *Urban Transport and the Environment in the 21st Century*. WIT Press, 2012. Accessed: Jan. 18, 2022. [Online]. Available: https://www.witpress.com/books/978-1-84564-580-9

[6] S. Lee and Y. H. Cho, ‘Development of bending fatigue test system for trolley line simulating real conditions’, in *Proceedings of the KSR Conference*, The Korean Society for Railway, 2011, pp. 3059–3064.

[7] J. P. Bianchi, E. Balmes, and M.-L. N guyen-Tajan, ‘Dynamic stress prediction in catenary wires for fatigue analysis’, *The Dynamics of Vehicles on Roads and Tracks - Proceedings of the 24th Symposium of the International Association for Vehicle System Dynamics, IAVSD 2015*, no. October, 2016, doi: 10.1201/b21185-160.

[8] L. Chen, P. Peng, and F. He, ‘Fatigue life analysis of dropper used in pantograph-catenary system of high-speed railway’, *Advances in Mechanical Engineering*, vol. 10, no. 5, May 2018, doi: 10.1177/1687814018776135.

[9] D. Anastasio, A. Fasana, L. Garibaldi, and S. Marchesiello, ‘Analytical investigation of railway overhead contact wire dynamics and comparison with experimental results’, *Mechanical Systems and Signal Processing*, vol. 116, pp. 277–292, Feb. 2019, doi: 10.1016/j.ymssp.2018.06.021.

[10] O. Sunar and D. Fletcher, ‘Experimental Investigation on the Arc Damage and Fatigue Crack Initiation Risk of Copper-Silver Contact Wires’, *IEEE Transactions on Power Delivery*, pp. 1–8, 2022, doi: 10.1109/TPWRD.2022.3198734.

[11] Z. Wenxuan, M. Meijun, W. Jing, and W. Haiying, ‘Research on Contact Wire Uplift of Typical High-speed Railway at 300km/h and 350km/h’, in *2021 IEEE 2nd China International Youth Conference on Electrical Engineering (CIYCEE)*, Chengdu, China: IEEE, Dec. 2021, pp. 1–6. doi: 10.1109/CIYCEE53554.2021.9676903.

[12] S. Gregori, M. Tur, E. Nadal, and F. J. Fuenmayor, ‘An approach to geometric optimisation of railway catenaries’, *Vehicle System Dynamics*, vol. 56, no. 8, pp. 1162–1186, Aug. 2018, doi: 10.1080/00423114.2017.1407434.

[13] Y. Kim *et al.*, ‘Fatigue life prediction method for contact wire using maximum local stress’, *Journal of Mechanical Science and Technology*, vol. 29, no. 1, pp. 67–70, Jan. 2015, doi: 10.1007/s12206-014-1210-3.

[14] Z. Guo *et al.*, ‘Fatigue life estimation of cold drawn contact wire’, *International Journal of Precision Engineering and Manufacturing*, vol. 15, no. 11, pp. 2291–2299, Nov. 2014, doi: 10.1007/s12541-014-0593-5.

[15] S. H. Kim, R. H. Bae, and J. D. Kwon, ‘Bending fatigue characteristics of wire rope’, *Journal of Mechanical Science and Technology*, vol. 26, no. 7, pp. 2107–2110, Jul. 2012, doi: 10.1007/s12206-012-0524-2.

[16] J. P. Massat, T. M. L. Nguyen-Tajan, H. Maitournam, E. Balmès, A. Bobillot, and J.-P. Massat, ‘Fatigue analysis of catenary contact wires for high speed trains’, in *9th Word Congress on Railway Research WCRR*, Lille,France: 9th Word Congress on Railway Research WCRR, 2011.

[17] J. Kohlhaas, ‘Interoperable overhead contact line SICAT H1.0 for high-speed line Cologne-Rhine/Main; Interoperable Oberleitung SICAT H1.0 der Schnellfahrstrecke Koeln-Rhein/Main’, *Elektrische Bahnen - EB*, vol. 100, no. 7, pp. 249–257, 2002.

[18] T. Popa, L. Anghel, B. Cernat, R. Hrin, and D. Buretea, ‘Collaborative project H2020-MG-2015-2015 GA-636237’.

[19] Furrer+Frey, ‘Series 1 The Great Western Railway Electrification Project Technical Report’, Bern, 2014.

[20] F. Kiessling, P. Rainer, A. Schmieder, and S. E, *Contact Lines for Electric Railways*. Siemens, 2009.

[21] G. Zhen *et al.*, ‘Bending fatigue life evaluation of Cu-Mg alloy contact wire’, *International Journal of Precision Engineering and Manufacturing*, vol. 15, no. 7, pp. 1331–1335, 2014, doi: 10.1007/s12541-014-0473-z.

[22] O. Sunar, ‘Arc Damage Identification and Its Effects on Fatigue Life of Contact Wires in Railway Overhead Lines (PhD Thesis)’, The University of Sheffield http://etheses.whiterose.ac.uk/28205/ ISNI:0000 0004 9356 9895, 2021. [Online]. Available: http://etheses.whiterose.ac.uk/28205/

## Resume

**Özgün SUNAR**

After obtaining his BSc and MSc degrees from Mechanical Engineering in Turkey, he got his PhD degree at The University of Sheffield, United Kingdom, Department of Mechanical Engineering. He primarily conducts studies on fatigue, fracture mechanics, materials science and finite element analysis. He has been working as an assistant professor at Eskisehir Technical University since 2021.

E-mail: ozgunsunar@eskisehir.edu.tr

## Ethics Statement:

Authors confirm that the article is original, there is no plagiarism issue.