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Estimations of stress concentration factors C_w/K_{ts} for helical circular/square cross sectional tension-compression springs and artificial neural network modelling

Helisel daire/kare kesitli çekme-basma yayları için gerilme yığılma faktörü (Cw/Kts) nün yapay sinir ağı modeliyle tahmin edilmesi

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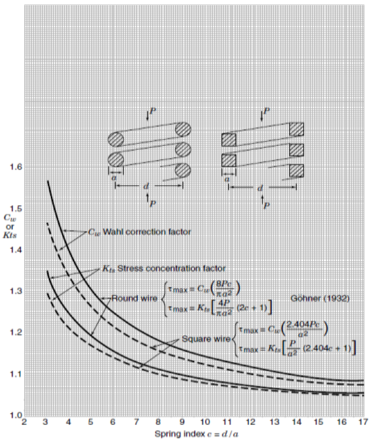
Estimations of Stress Concentration Factors (C_w/K_{ts}) for Helical Circular/Square Cross Sectional Tension-Compression Springs and Artificial Neural Network Modelling

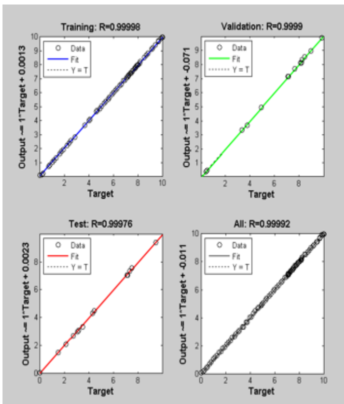
Highlights

- *Stress concentration factor (Cw/Kts)*
- *Helical circular/rectangular springs design*
- *Artificial neural networks (ANN)*
- *Circular and square cross sectional tension-compression springs*

Graphical Abstract

In this study contains stress concentration factor for Circular / Square Cross sectional Springs. Experimental results collected and a ANN model was developed.





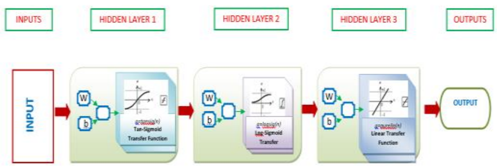


Chart. A **Figure. A** **Figure. B**

Aim

This study is the determination of stress concentration factor (Cw / Kts) with artificial intelligence technique for circular and square cross-sectional springs

Design & Methodology

Experimental results were digitized and an ANN model was developed for the related problem.

Originality

In the study, a new method has been presented for the precise and direct determination of the stress concentration factor (Cw / Kts), which has been obtained by experimental studies before, without any digitization, determined by the graphic reading technique.

Findings

It is provided to determine the stress stress factor (Cw / Kts) easily for circular or square cross section springs.

Conclusion

Stress concentration factor (Cw / Kts) for springs with different cross-sectional shapes is provided to be defined easily and quickly, without being dependent on any table or equation.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission

Helisel Daire/Kare Kesitli Çekme-Basma Yayları İçin Gerilme Yığılma Faktörünün (Cw/Kts) Yapay Sinir Ağı Modeliyle Tahmin Edilmesi

Araştırma Makalesi / Research Article

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ÖZ

Yaylar, makine tasarımında yük altında göstermiş oldukları elastik deformasyon karakteristikleri ve enerji depolama özelliklerinden dolayı çok farklı amaçlar için kullanılırlar. Yayların birçok çeşidi ve farklı profil şekilleri mevcuttur. Dairesel kesitli, düşük helis adımlı helisel bir çekme-basma yayı için, Wahl faktörü (Cw), yay tasarımı için genellikle yay telinin eğrilik yarıçapı ve kayma gerilmesi kullanılır. Dairesel kesitli bir çekme-basma yayının gerilme yoğunluğu faktörünün belirlenmesi için, nominal kayma gerilmesi τ_{nom}; burulma (τ) ve kesme gerilmelerinin (τ) toplamı biçiminde mukavemet teorileri dikkate alınarak hesaplanır. Kare kesitli bir çekme-basma yay içinde yine gerilme yoğunluğu faktörünün belirlenmesi için, nominal kayma gerilmesi τ_{nom}; burulma (τ) ve kesme gerilmelerinin (τ) toplamı biçiminde mukavemet teorileri dikkate alınarak hesaplanır. Tasarım hesaplamalarında daha kolay bir metod olan Wahl faktörünün kullanılması tavsiye edilmektedir. Cw veya Kts kullanılsa da aynı maksimum değer elde edilir. . Bu çalışmada, gerilim yoğunluk faktörü ve Wahl faktörünün belirlenmesini ihtiva etmektedir. Bu amaçla dairesel ve kare kesitli yaylar için daha önceden deneysel olarak elde edilmiş olan gerilme yığılma faktörü eğrileri sayısal hale dönüştürülmüştür. Bu sayısal veriler bir excel tablosunda tasnif edilmiştir. Elde edilen excell verileri kullanılarak bir YSA (Yapay Sinir Ağı) modeli geliştirilmiştir., Yay tasarımı için gerilme yığılma ve Wahl faktörünün belirlenmesi için kolay ve kullanışlı bir metod olan YSA modeli sunulmuştur.

Anahtar Kelimeler: Gerilme yoğunluk faktörü (Cw/Kts), yay, yapay sinir ağı (YSA).

Estimations of Stress Concentration Factors (Cw/Kts) For Helical Circular/Square Cross Sectional Tension-Compression Springs And Artificial Neural Network Modelling

ABSTRACT

Springs are used for various purposes in machine design as they can store energy under load, due to their elastic deformation characteristics. There are many types and profiles of springs. For a round wire helical compression or tension spring of small pitch angle, the Wahl factor, a correction factor (Cw) taking into account curvature and direct shear stress, is generally used in the design. The corresponding stress concentration factors, which may be useful for mechanics of materials problems, are obtained by taking the nominal shear stress τ_{nom} as the sum of the torsional stress (τ) and the direct shear stress (τ) for round wire. In the case of the wire of square cross-section, τ_{nom} is the sum of the torsional stress and the direct shear stress. For design calculations it is recommended that the simpler Wahl factor be used. The same value of max will be obtained whether one uses Cw or Kts. This study contains the determination of stress concentration factor and Wahl factor. For this aim, stress concentration factor charts were converted numerical values for round and square wires. These values were collected in an excel file. ANN (Artificial Neural Networks) model was developed using the data. It is an easy and convenient method, ANN model, was presented for the determination of stress concentration and Wahl factor for spring design.

Keywords: Stress concentration factor(Cw/Kts), spring, artificial neural network(ANN).

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1. INTRODUCTION

Stress concentration is one of the most important factors to be considered in the design of machine elements. Generally, the parts of the machine are subject to difficulties according to their location. This leads to regions where the machine part is deformed suddenly depending on the shape of the machine part. The basic principle in design; the maximum stress in the material where the stress value does not exceed the design material resistance is considered to be performed correctly in a logical framework.

Springs are flexible machine elements used for controlled application of force (or torque) or for storing and release of mechanical energy. Flexibility (elastic deformation) is enabled due to cleverly designed geometry or by using flexible material. Generally, coils of loaded spring are under combined stress (compression/tension, bending, torsion and shear). In most cases springs have relatively small helix angle and small Spring index (C=D/d), therefore compression stress and bending stress can be omitted. Maximum stress can be computed by the superposition of torsion stress and direct shear stress. The curvature of the wire (helix shape) increases the stress on the inside of the spring and decreases it on outside. Curvature effect together with shear-stress augmentation factor can be defined by Wahl factor or Bergsträsser factor. Because the results of these factors differ by less than 1%, Bergsträsser factor is preferred. Stresses in the hook ends of tension springs are usually higher than stresses in the coils of the spring. Stress-augmentation factors are used to determine these stresses. An analytical approach is not so developed for rectangular wire like for round wire. Parameters from tables etc.

The first studies about springs were performed by Haringx (1948), Wahl (1963), Mottershead (1980), Cook and Young (1985), Belingardi (1988), Haktanir and Kiral (1993), Haktanir (1994, 1995) and Alghamdi (1991), Omurtag and Akoz (1992), Akoz and Kadioglu (1996) and Batoz and Triki (1995) [1-12]. In the literature some of the numerical studies and the other were used new methods FEM, BEM etc for stress – strain, curvature pitch, distorsion to different loading conditions. Fundamental reference belongs to Wahl who was investigated wire of the spring as a round bar under the a shear and torque states. The later studies were for a rectangular cross-section helical compression spring using 3D stiffness matrix method. Spring stiffness was determined using strain energy methods and 2th Castigliano theorem. In this study was included a geometric form of springs; pitch, a curvature of wire according to bending and twisting moments and shear force [13]. Forrester determined the three-dimensional stiffness matrix of a rectangular cross-section helical compression spring. The stiffness of this spring is derived using strain energy methods and Castigliano's second theorem. The resulting stiffness takes into account the bending moments, the twisting moments, and the transverse shear forces [14]. In addition, the spring's geometric form which includes the effects of pitch, the curvature of wire and distortion are taken into consideration. Then a finite element model was generated and the stiffness matrix was evaluated by applying a unit load along the spring's axis. Stress analysis is also one of the themes of research in helical springs. Investigations in this area began early with Ancher and Goodier who used the boundary elements method to apply the elasticity theorem and to develop an approximation result to satisfy governing equations and boundary conditions along the surface of the coil [15 -17]. Kamiya and Kita were investigated the spring helical angle using BEM method [18]. Jiang and Henshell were researched stress problems in circular cross-section helical springs.A general and accurate fnite element model for a circular cross-sectional spring subject to axial loads (extension or/and torsion) was developed using FEM methods [19, 20].

Kotaro Watanabe et al. a new type rectangular wire helical spring was contrived by the authors is used as suspension springs for rally cars, the stress was checked by FEM analysis theory on the twisting part. The spring characteristic of the suspension helper spring in a body is clarified. Manufacturing equipment for this spring is proposed [21].

Gumus et al, a software was designed about the design of helical spring. A wide range of information was given in this program about spring samples, spring materials, spring equations, spring standards, spring producing, spring producers. In calculate the part of the program, the force-displacement calculations of helical compression and extension spring were done whose wire diameter, body diameter, coil number was defined. Also, restricts were given as outer diameter, inner diameter to these springs so it was realized spring dimensions were optimized to minimum outer volume or minimum material. In addition, the deformation analysis of helical coil spring was done and the obtained spring index values were compared to values obtained from the equation. The obtained datas were added to program [22].

Different methods were used in the literature to determination of stress concentratin factor. Among the one is Artificial Neural Network Methods besides FEM, BEM, numerical solution etc.

In this study aim is determination of the stress factors Cw and Kts for helical round or square wire compression or tension springs. The stress concentration factor was modelled with an ANN. Emprical (charts) data and ANN model performance were compared with each other.

2. MATERIAL AND METHOD

In this study, stability conditions of machine elements against stress in terms of stress concentration are examined in general. To what extent the machine parts can be challenged depends on the strength of the product, the design of the product and the material properties. Machine parts can be found under different difficulties according to work environments. The irregularities in shape, the channels, the notches the design of the machine element can change the stress of the product. Different methods (FEM, photoelastic, experimental numerical, statistical, artificial intelligence techniques, etc.) were used to investigate the stress conditions of the machine element in more detail.

Previously obtained from experimental and validated data tables are already available and are used in the design. The main problem here is that there are no mathematical formulas for these tables. The user only obtains these values by reading the relevant table. Value reading from the table is a very tedious and error-prone process. The values obtained vary from user to user. Since these are required for each user to obtain the same amount and these have been converted into numerical values from graphics with high computer technology software. Converted numerical values were classified in an excel file according to their origin. A new ANN model was created in the sensitivity that the classical regression model can not reach. It is necessary to increase the equation of degree to improve the sensitivity of the formula in the classical regression. When degree of equation increases, calculation becomes quite difficult to obtain a result by using these equations. The user has the advantage of obtaining direct results without having use any formulas prepared software in Matlab. A helical spring may be regarded as a curved bar subjected to a twisting moment and a direct shear load [23]. The final paragraph in the preceding section applies to helical springs. For a round wire helical compression or tension spring of small pitch angle, the *Wahl* factor, C_w, a correction factor taking into account curvature and direct shear stress, is generally used in design (see Chart 1) [2, 25].

For round wire;

$$C_w=\frac{\tau_{max}}{\tau}=\frac{4c-1}{4c-4}+\frac{0.615}{c} \quad (1)$$

$$\tau=\frac{\tau(a/2)}{J}=\frac{P(d-2)}{\pi a^3/16}=\frac{8Pd}{\pi a^3}=\frac{8Pc}{\pi a^2} \quad (2)$$

where T is the torque, P is the axial load, c is the spring index d/a, d is the mean coil diameter, a is the wire diameter, and J is the polar moment of inertia. For square wire $b=h=a$ the shape correction factor α is α=0.416 [29]. Here a is the width and depth of the square wire. Then 1/α =2.404 and

$$C_w=\frac{\tau_{max}}{\tau} \quad (3)$$

$$\tau_{max}=\tau(1+\frac{1.2}{c}+\frac{0.56}{c^2}=\frac{0.5}{c^3}) \quad (4)$$

$$\tau=\frac{Pd}{\propto a^3}=\frac{2.404Pd}{a^3}=\frac{2.404Pc}{a^2} \quad (5)$$

The corresponding stress concentration factors, which may be useful for mechanics of materials problems, are obtained by taking the nominal shear stress τ_{nom} as the sum of the torsional stress τ of Eq. (2) and the direct shear stress $\tau=4P/\pi a^2$ for round wire. In the case of the wire of square cross section, τnom is the sum of the torsional stress of Eq. (5) and the direct shear stress $\tau=P/a^2$. For round wire,

$$K_{ts}=\frac{\tau_{max}}{\tau_{nom}}=K_{ts}=\frac{\left(\frac{8Pd}{\pi a^3}\right)[(4c-1)/(4c-4)]+4.92P/\pi a^2}{8Pd/\pi a^3+4P/\pi a^2} \quad (6)$$

$$K_{ts}=\frac{2c[(4c-1)/(4c-4)]+1.23}{2c+1}$$

$$\tau_{max}=K_{ts}\left[\frac{4P}{\pi a^2}(2c+1)\right] \quad (7)$$

$$K_{ts}=\frac{\left(\frac{2.404Pd}{a^3}\right)(1+\frac{1.2}{c}+\frac{0.56}{c^2}+\frac{0.5}{c^3})}{2.404Pd/a^3+P/a^2}$$

$$K_{ts}=\frac{2.404c(1+\frac{1.2}{c}+0.56/c^2+0.5/c^3}{2.404c+1} \quad (8)$$

$$\tau_{max}=K_{ts}\left[\frac{P}{a^2}(2.404c+1)\right] \quad (9)$$

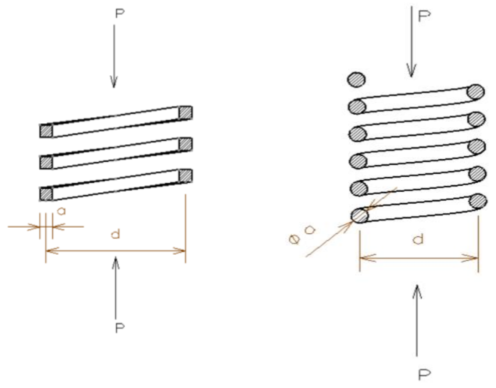

Figure 1. Model of for helical round or square wire

Values of C_w and K_{ts} are shown in Chart 1. K_{ts} is lower than the correction factor C_w. For design calculations it is recommended that the simpler Wahl factor be used. The same value of τmax will be obtained whether one uses C_w or K_{ts}. The effect of pitch angle has been determined by Ancker and Goodier [24]. Up to 10° the effect of pitch angle is small, but at 20° the stress increases sufficiently so that a correction should be made.

3 ARTIFICIAL NEURAL NETWORK(ANN) MODEL

ANN is a sub-field of Artificial Intelligence. ANN has a mathematical operational context in its back ground. ANN works with different learning algorithms. A neuron is the basic element of ANN. Neurons duties, shapes and sizes can be varied. Neurons activities are important. An ANN may be seen as a black box which contains hierarchical sets of neurons (e.g., processing elements) producing outputs for certain inputs. Each processing element consists of data collection, processing the data and sending the results to the relevant consequent element. The whole process may be viewed in terms of the inputs, weights, the summation function, the activation function and outputs (Figure 2) [26-31]. A neural network usually consists of inputs layer, hidden layers, and output layers (Figure 2). In this study contains stress concentration factors Cw and Kts for helical round or square wire compression or tension springs. Peterson's stress concentration factor charts [2, 25] were investigated. These charts are drawn as a result of the experimental study and are not identified by a mathematical function. These charts are still used today to define the stress concentration. It is necessary to read the data in these curves when defining the stress concentration for a particular problem. Value reading from the table is a very tedious and error-prone process. The values obtained vary from user to user. Since these are required for each user to obtain the same amount and these have been converted into numerical values from graphics with high computer technology software.

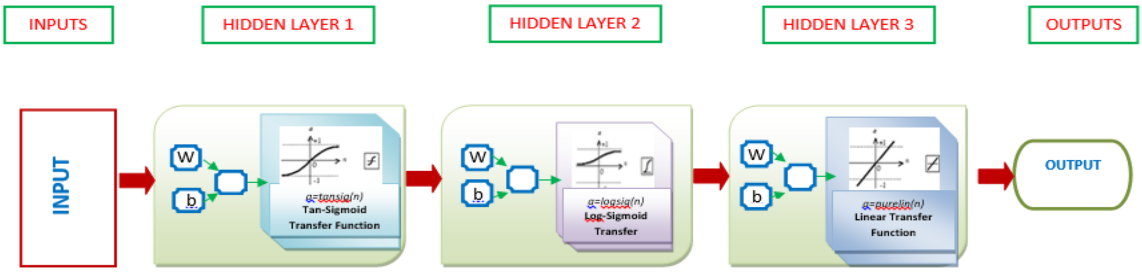

Figure 2. Basic artificial neural network model

Numerical data was created for these curves. An ANN database was created using these data and a new ANN model was developed. The data were obtained according to study parameters that have 1853 lines x 3 columns. Among them, 30% of data have been randomly selected and used as the test data and the other 70 % data were used training data. Profile type (rounded / square), ***c=d/a*** and $\boldsymbol{C_w}$ or $\boldsymbol{K_{ts}}$ (Table 1) [2, 25] are determination of the stress concentration factor C_w and K_{ts} for helical compression or tension springs of round or square wire.

Table 1. Stress concentration factors C_w and K_{ts} for helical round or square wire compression or tension springs

Profile type	***c=d/a***	***C_w or K_{ts}***
Square – wire		1.13
Rounded - wire	3-17	1.8

These parameters were used as input-layer, LM (Levenberg-Marquardt) algorithm and MLP (Multi Layer Perception) were used in the ANN model. Profile type (rounded / square), c=d/a were used as input-layer and C_w or K_{ts} were used as output-layer of the ANNs. In the ANN model, tansig, logsig and purelin transfer functions (f) have been used and expressed as follows (Eqs 10-13) [26-31]:

$$NET_i = \sum w_{ij}.x_j + w_{bi} \tag{10}$$

$$a = \text{tansig}\,(n) = \frac{2}{(1+e^{-2n})} - 1 \tag{11}$$

$$a = \text{logsig}\,(n) = \frac{1}{(1+e^{-n})} \tag{12}$$

$$a = \text{purelin}\,(n) \tag{13}$$

n: Number of processing elements in the previous layer where NET is the weighted sum of the input.

An ANN model was developed using Matlab NN tool. For this aim a new ANN code has been prepared and developed. Different models have been tested. The best model was determined. Figure 3 shows Improved an ANN Model using MATLAB. Figure 4 shows the best training performance of ANN model. Figure 5 shows Training performance of ANN and Figure 6 shows the best validation performance of ANN. Figure 7 shows. Error Histogram of ANN and Figure 8 shows The ANN predictions; Training, Test and Validation performance. These figures have been getting from prepared Matlab code. ANN model results were compared with the statistically. Table 2 shows Statistical Performance of Training Step. The back propagation learning algorithm has been used with Scaled Conjugate Gradient (SCG) learning algorithm and Levenberg-Marquardt (LM) learning algorithm versions at the training and testing stages of the Networks. The number of hidden layers and the number of neurons for each hidden layer were determined. Then, the number of iterations were entered by the user, and the training starts. The training continues either to the end of the iterations or reaching the target level of errors.

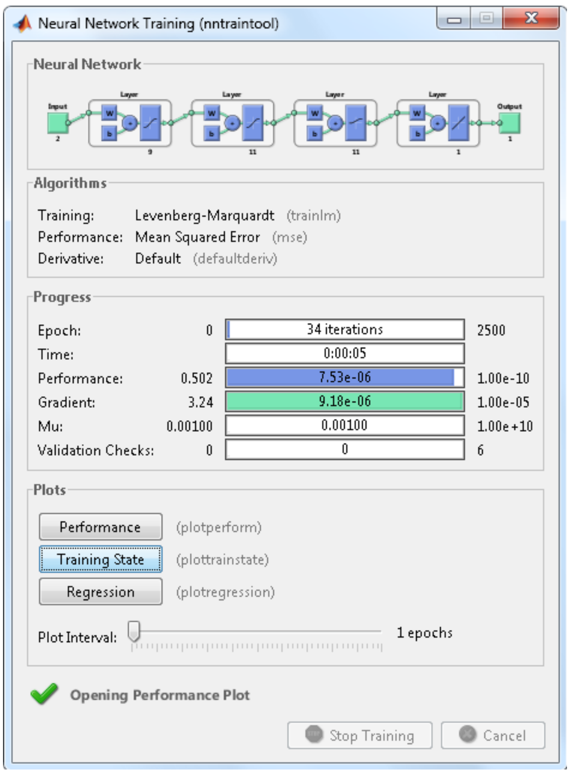

Figure 3. Improved an ANN Model using MATLAB

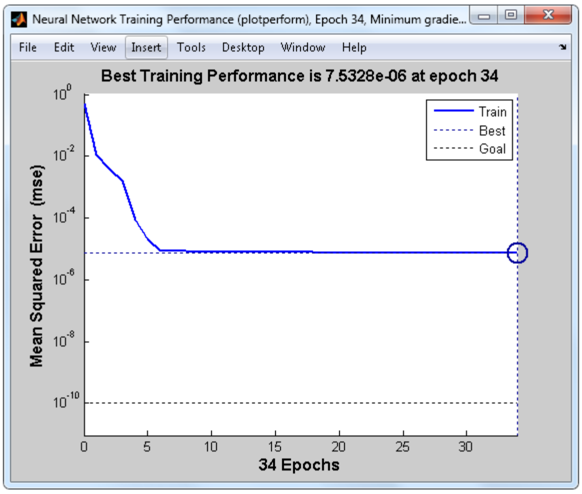

Figure 4.. Best Training performance of ANN model

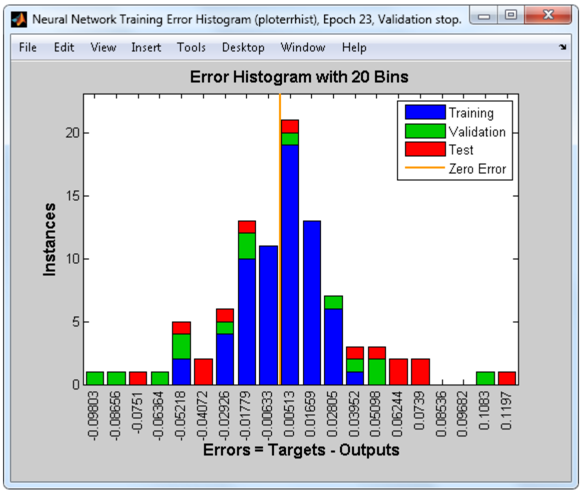

Figure 7. Error Histogram of ANN

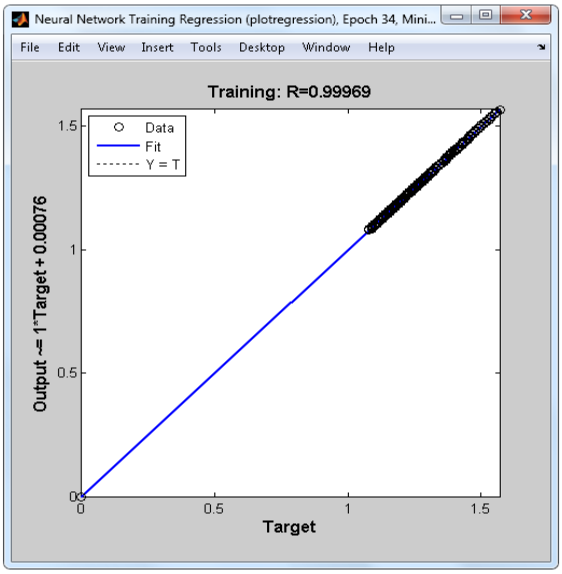

Figure 5. Training performance of ANN model

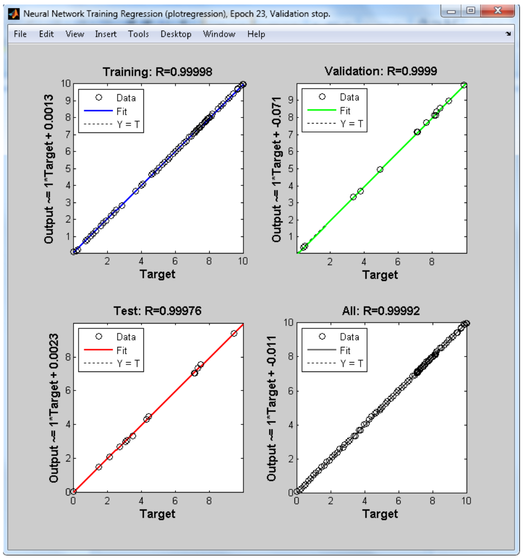

Figure 8. The ANN predictions; Training, Test and Validation performance

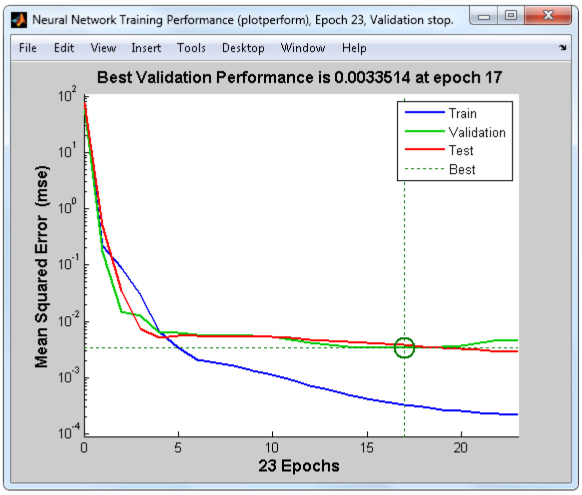

Figure. 6. Best validation of ANN

Table 2. Training Statistical Performance of ANN model

Absolute Fraction of Variance (R^2)	Root Mean Square Error (RMSE)	Mean Error Percentage (MEP %)
0.99999980	0.00049403	0.03444225

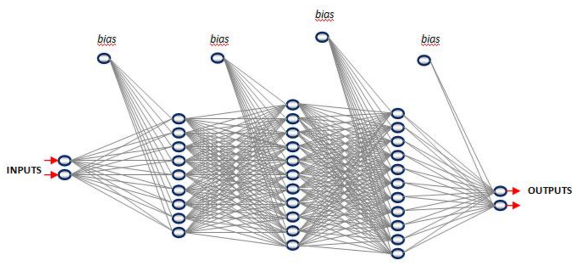

Figure 9. ANN architecture with [2 9 11 11 2] processing elements at three hidden layers

4. TESTING THE ACCURACY OF ANN MODELLING

To understand an ANN modelling is making good predictions, the test data which has never been presented to the network is used and the results are checked at this stage. The statistical methods of R^2, RMSE and MEP values have been used for making comparisons [26-31]. The same data obtained from the regression analysis is used to determine the mentioned values. These values are determined by the following Eqs (14-16):

$$RMSE = \left((1/p) \sum_j |t_j - o_j|^2 \right)^{1/2} \quad (14)$$

$$R^2 = 1 - \left(\frac{\sum_j (t_j - o_j)^2}{\sum_j (o_j)^2} \right) \quad (15)$$

$$MEP = \frac{\sum_j \left(\frac{t_j - o_j}{t_j} \times 100 \right)}{p} \quad (16)$$

Using the trial error method, the structure of the network (i.e. the number of neurons and hidden layers) is altered and the training operation is repeated. To be able to get accurate results we have used four hidden layers and for each hidden layer. we have changed number of neurons used at each hidden layer (e.g. from 5 to 150) to get the best network in terms of the statistical errors that it provides.

Figure 10 shows Cw or Kt values were determined according to profile type (rounded / square), c=d/a . Figure 10 shows comparison of emprical values (chart values) and ANN model values. Figure 10 shows comparison of emprical values (chart values) and ANN model values. Both ANN models results and emprical values were compatibled with each other.

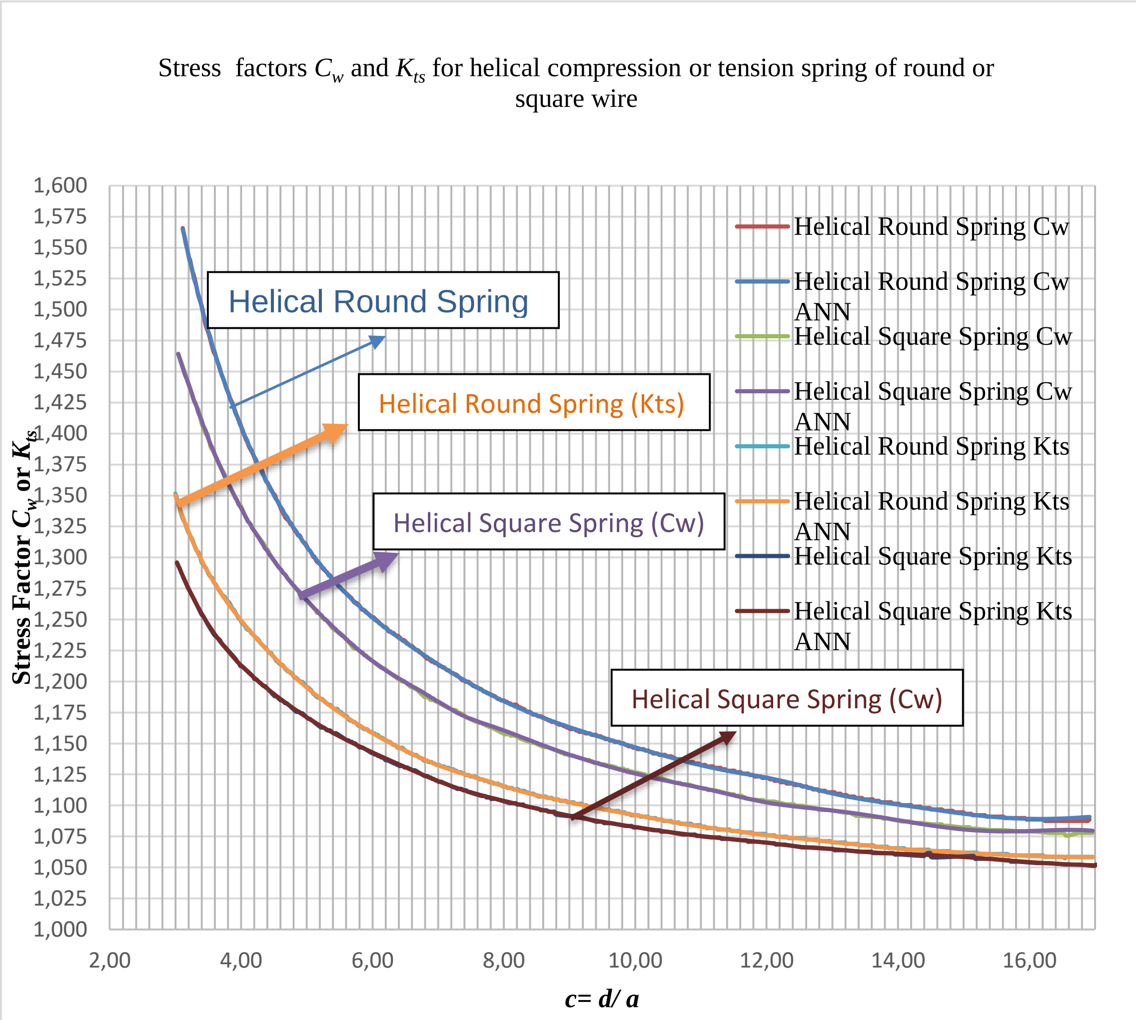

Figure 10. Comparison of Emprical and ANN model of Stress factors C_w and K_{ts} for helical compression or tension springs of round or square wire (from mathematical relations of Wahl 1963)

5. RESULTS AND DISCUSSION

In this study, we have composed the chart data and network predicted output results Profile type (rounded / square), ***c=d/a*** and C_w or K_{ts} for the stress concentration factor parameters for statistical error analyzing methods. As presented in Table 2, the statistical error levels for both training and testing data sets are evaluated. As the table illustrates the network with hidden layers of [2 9 11 11 2] neurons at each layer has provided the best results (Figure 9).

Following, the ANN model as illustrated in Figure 9 set up using 2 input layers and with 9 11 11 processing elements at three hidden layers and finally 2 output layers are used. The representation of knowledge is accomplished by the weights in between the layers. In terms of the statistical error analysis methods, using Levenberg-Marquardt (*LM*) learning algorithm technique for Outputs.

Figure 10 shows ANN architecture [2 9 11 11 2]. Figure 10 shows empirical data and ANN data graphs. Emprical data and ANN modelled data compatible with each other.

6. CONCLUSION

In this study contains stress concentration factor determination using Peterson's Stress Concentration Factor charts [2, 31] and ANN modeling. Peterson's graphs have been accepted as scientifically valid, but a mathematical equation has not yet been transformed. Peterson's charts were drawn as a result of the experimental study and were not identified by a mathematical function. The values in these graphs can be defined only with the result of experimental studies. It is easier and more practical to determine these values using auxiliary software instead of using formulas. These charts are still used today to define the stress concentration factor. It is necessary to read the data in these curves when defining the stress concentration for a particular problem. These curves have been converted into numerical values with the help of highly sensitive computer software. An ANN database was created using these data. A new ANN model was developed using Matlab software. Different ANN models were tried and the best model was determined for stress concentration factors C_w and K_{ts} for helical round or square wire compression or tension springs according to profile type (rounded / square), ***c=d/a*** and C_w or K_{ts} parameters. The ANN model was provided high accuracy for prediction of stress factor **Cw** and Kt. This model has R^2= 0.99999980 MEP% =0.03444225 and RMS=0.00049403. Users can be read fault value that getting from chart. Using the ANN model these faults were eliminated. The easy and economical method was improved using an ANN model. This model an effective and usefull method. This method can be used with more reliability. ANN model was improved for stress factor C_w and K_{ts} for helical round and square wires.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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Annex:

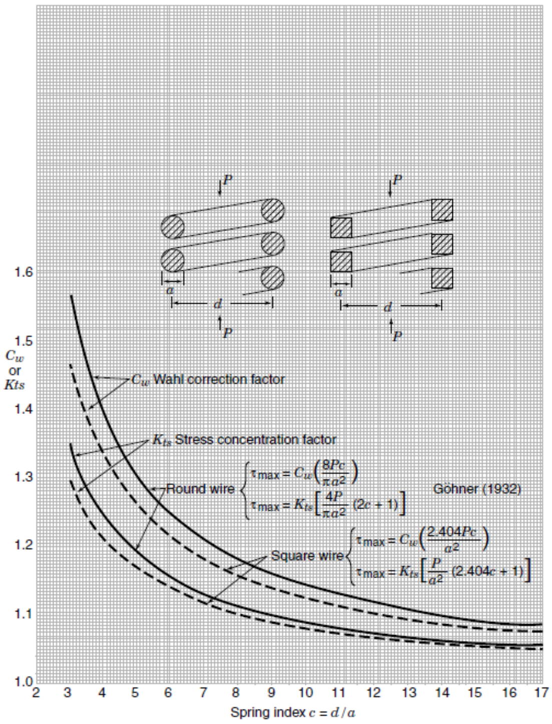

Chart 1. Stress factors C_w and K_{ts} for helical compression or tension springs of round or square wire [2, 25]