# Load-Carrying Capacity of Patch-Loaded Stiffened Steel Plate Girders

**Ahmed Sagban Saadoon Abdulnasser Mohammed Abbas Ali AbdulhasanKhalaf**

*Civil Engineering Department, College of Engineering, University of Basrah, Iraq*

ahmsag@gmail.com nasser21272@gmail.com ali_abd575@yahoo.com

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## Abstract

This research is aiming to establish an alternative model for determining the ultimate patch load of plate girders with longitudinal stiffener. The proposed model is based on empirical equations and regression analysis and verified with a wide database domain that exists in the literature. A comparison between the results obtained from the proposed model and those obtained from the BS 5400 code specifications is also made in this study. It is found that the proposed model shows a very good agreement with the test results and it is more quite accurate than the BS 5400 code predictions.

**Key words**: Plate girders, Stiffened webs, Load-carrying capacity, Regression analysis.

## 1. Introduction

Steel girders are often being under the action of concentrated loads, commonly, called patch loading. Patch loading (or partial edge loading) of steel girders, is a load case in which a concentrated vertical force is perpendicularly subjected to the top flange of a girder. This case of loading usually causes a local failure of the web, in the vicinity region of the loaded flange. Thus, the determination of the ultimate patch load is very important for economic and safety purposes. Usually, stiffeners are utilized to maximize the resistance of the patch loading, as in the bridges or crane girders case. During incremental loading, vertical stiffeners are not an adequate solution, since the applied patch load is moved freely throughout the girders span. Therefore, longitudinal stiffening is used, especially in large girders, to increase the load-carrying capacity (resistance) for the steel plate girders (webs) that subjected to patch loading or concentrated loads, as shown in Fig. (1). The longitudinal stiffeners commonly placed adjacent to the top compression flange, which is exposed to a negative bending, in order to enhance the strength of plate girders and to prevent lateral deflections of the web, and hence, to reduce the secondary effects, which may cause a failure due to breathing of the web [1].

Patch loading is a well-known phenomenon that has been studied theoretically and experimentally by many researchers [2] – [15]. Many proposals (model) have been presented to formulate the patch loading of stiffened plate girders. Some of these proposals are empirical models based on a regression analysis, while some are based on failure mechanisms analysis. Also, there are various models based on soft computing techniques such as neural networks, fuzzy logic, neuro-fuzzy system, and genetic logarithms.

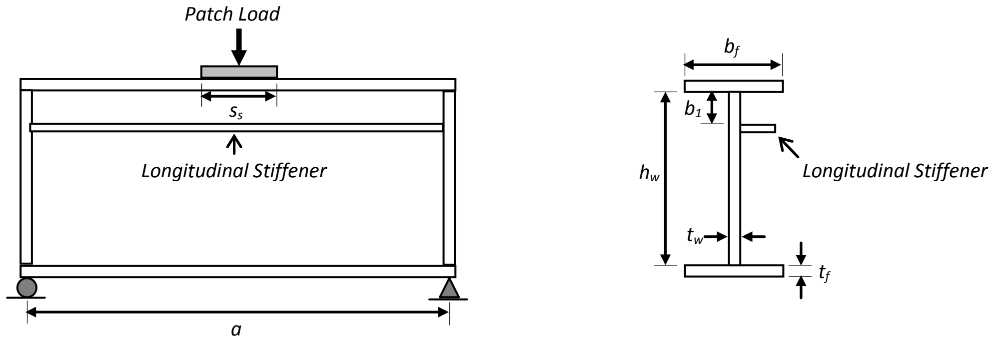



**Figure (1) Plate girder with longitudinal stiffener**

## 2. Literature Review

Many investigations have been conducted to study the longitudinal stiffeners effect on patch loading resistance for the plate girders. Some researchers [2] – [6] proposed regression models related the capacity of patch loading for longitudinal stiffened webs with that of unstiffened webs by multiplying the last by a correction factor, which is, a function of the stiffener position. From the deformed configuration at failure, Roberts and Rockey [7] utilized the yield line mechanism to demonstrate the failure pattern of plate girders under patch loading. They proposed a model for the ultimate strength calculation of unstiffened slender plate girders. Their model was established on a yield line mechanism which composing of four plastic hinges in the top flange and three yield lines in the web, as shown in Fig. (2). Later, this model was modified by Roberts and Newark [8] by changing the yield lines position in the web to be at approximately forty times of web thickness. Graciano and Edlund [9] improved Roberts and Newark's model by making an assumption regarding the stiffener flexural rigidity. Lagerqvist and Johansson [5] adopted a post-critical resistance approach to propose a model using buckling curves for the patch loading strength. Graciano and Johansson [10] proposed a model in the sense of the design methodology of the Eurocode 3 Part 1.5 [16] to take into account the presence of longitudinal stiffeners. Using soft computing programs, Fonseca et al. [11] developed a neural network to predict the ultimate patch load. Fonseca et al. [12] have also used a neural model to carry out parametric studies of patch loading resistance. Also, a neuro-fuzzy system was used by Fonseca et al. [13] for a parametric analysis in this subject. Cevik [14] proposed a soft model based on genetic programming for patch loading strength. Recently, Cevik et al. [15] formulated a model to calculate the ultimate strength of longitudinally stiffened plate girders using stepwise regression.

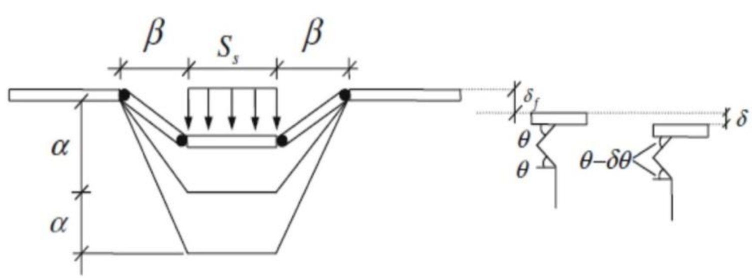



**Figure (2) Yield line mechanism [7]**

## 3.Regression Models

To take into account the influence of the longitudinally stiffener on the girders carrying capacity, it has been customary to relate the resistance of patch loading for longitudinal stiffened webs $F_s$ with plate girders that unstiffened $F_{un}$, by multiplying the last with a magnification factor $f_s$,

$$F_s = F_{un} . f_s , \tag{1}$$

Where the factor $f_s$ depends mainly on the stiffener position $(b_1 / h_w)$ (see Fig. 1). This factor was usually obtained on the form $A + B(b_1 / h_w)$ or $A + B \ln(b_1 / h_w)$, where $A$ and $B$ are two constants estimated by regression analysis.

Janus et al. [2] proposed a magnification factor for the consideration of the stiffener. The factor was based on an empirical formulation of the stiffened web. Kutmanova and skaloud [3] made some improvements to the formulation presented by Janus et al. and proposed the following formula

$$F_{un} = 12.6 f_{yw} t_w^2 . \left[ 1 + 0.004 \left( \frac{s_s}{t_w} \right) \right] . \left[ \left( \frac{I_f}{t_w^4} \right) \sqrt{\frac{f_{yf}}{240}} \right]^{0.153} , \tag{2}$$

$$f_s = 0.958 - 0.09 \ln \left( \frac{b_1}{h_w} \right), \tag{3}$$

where $I_f$ is second moment of inertia of the flange.

Markovic and Hajdin [4] obtained a simple linear equation for the consideration of the stiffener

$$F_{un} = 0.5 t_w^2 \sqrt{\frac{E f_{yw} t_f}{t_w}} . \left[ 1 + \frac{3 s_s}{h_w} \left( \frac{t_w}{t_f} \right)^{3/2} \right] \sqrt{1 - \left( \frac{\sigma_b}{f_{yw}} \right)^2} , \tag{4}$$

$$f_s = 1.28 - 0.7 \left( \frac{b_1}{h_w} \right), \tag{5}$$

where $\sigma_b$ is bending stress. In Eq. (5), $f_s$ is restricted to lie between 1.0 and 1.21. This design method was integrated in BS 5400 Part 3 [17].

Lagerqvist and Johansson [5] developed the following design method for the resistance of patch loading of unstiffened plate girders

$$F_{un} = F_y . \chi \,, \tag{6}$$

$$F_y = f_{yw} t_w \left[ s_s + 2t_f \left( 1 + \sqrt{m_1 + m_2} \right) \right], \tag{7}$$

$$m_1 = \frac{f_{yf} b_f}{f_{yw} t_w}, \tag{8}$$

$$m_2 = 0.02 \left( \frac{h_w}{t_f} \right)^2 , \tag{9}$$

$$\lambda = \sqrt{\frac{F_y}{F_{cr}}} \,, \tag{10}$$

$$F_{cr} = k_f . \frac{\pi^2 E}{12(1-\nu^2)} . \frac{t_w^3}{h_w} \,, \tag{11}$$

$$k_f = 5.82 + 2.1 \left( \frac{h_w}{a} \right)^2 + 0.46 \left( \frac{b_f t_f^3}{h_w t_w^3} \right)^{0.25} , \tag{12}$$

$$\chi = 0.06 + \frac{0.47}{\lambda} \qquad \leq 1 , \tag{13}$$

where,

$F_y$ is yield resistance,

$m_1$ and $m_2$ are dimensionless factors ( $m_2 = 0$ for welded girders if $\lambda < 0.5$ ),

$\lambda$ is slenderness parameter,

$F_{cr}$ is buckling load,

$k_f$ is buckling coefficient, and

$\chi$ is resistance function.

When the applied moment $M_a$ is more than 50% of the resistance bending $M_r$ for the plate girder, it should be considered the interaction with bending moment. This design procedure is incorporated in the Eurocode 3 Part 1.5 [16].

Graciano [6] demonstrated that besides the stiffener location, the rate of the flange to web thickness, and the rate of the yield strength of the flange to yield strength of the web has also some influence on the patch loading resistance. Based on this analysis, a magnification factor for Eq. (6) was obtained as

$$f_s = 0.556 - 0.277 \ln \left[ \frac{b_1}{h_w} \left( \frac{f_{yf} / f_{yw}}{t_f / t_w} \right) \right] . \tag{14}$$

It should be mentioned that this model is restricted for ratios $(b_1 / h_w) \leq 0.3$.

## 4. Proposed Model

Many researchers presented different models, to formulate and estimate the longitudinal stiffening effect on the resistance of patch loading by using experimental results. In this study, the used experimental data, which contain 161 plate girders, are obtained from previous studies which collected by Graciano [1]. The proposed model includes the effects of all parameters that affect the ultimate strength of steel girder webs to patch loading. Generally, these parameters are usually determined by the nature of the problem. Eight major variables are chosen to formulate the proposed model. These variables and their ranges are listed in Table (1).

**Table (1) Range of parameters**

| *Parameters* | *Range* |
|---|---|
| Length of web panel( $a$ ) (mm) | 500 - 3000 |
| Distance between flange and stiffener ( $b_1$ ) (mm) | 50 - 327 |
| Width of flange ( $b_f$ ) (mm) | 50 - 300 |
| Flange yield stress ( $f_{yf}$ ) (MPa) | 235 - 485 |
| Web yield stress ( $f_{yw}$ ) (MPa) | 191 - 483 |
| Depth of web panel ( $h_w$ ) (mm) | 500 - 1275 |
| Length of patch load ( $s_s$ ) (mm) | 40 - 690 |
| Flange thickness ( $t_f$ ) (mm) | 5 - 40 |
| Web thickness ( $t_w$ ) (mm) | 2 - 6 |

In the present research, an attempt is made to propose a model that is valid for all ranges of parameters used in the test database where some previous models are not suitable if the specified ranges are exceeded, especially the ratio $(b_1 / h_w)$. The present modeling conducted in two steps. In the first step, some modification on the procedure incorporated in the Eurocode 3 is made. There is no need to calculate the resistance of the unstiffened web, Eq. (6), instead only the yield resistance is required, Eq. (7). While regression analysis, in the second step, is used to find the best empirical magnification factor. As a result, the following equations are proposed to estimate the resistance of stiffened plate girders.

$$F_s = F_y . f_s , \tag{15}$$

$$f_s = 0.556 - 0.277 . \frac{\ln\left[\left(\frac{b_1}{h_w}\right)\left(\frac{f_{yf} t_w}{f_{yw} t_f}\right)\right]}{\sqrt{\lambda^3}} , \tag{16}$$

where $F_y$ and $\lambda$ are calculated from Eqs. (7-12) for all values of the ratio $(b_1 / h_w)$.

## 5. Results and Discussion

Table (2) shows a comparison between the outcomes of the proposed model versus the actual experimental results, and their comparison to BS 5400 results for the entire the originally used test database. Statistical parameters of this comparison are also presented in the mentioned table. From this table, it can be seen that for the proposed model, the average values of ratios of test to predicted load is 0.996 with a standard deviation and variation coefficient of 0.136 and 13.65, respectively. While for the BS 5400 code the average values of ratios of test to predicted load are 1.512 with a standard deviation and variation coefficient of 0.243 and 16.07, respectively. Therefore, the results of the proposed model are closer to the used test data than those of the BS 4500 code. It is obvious that the BS 4500 procedure is too conservative and its variation, as can be seen in Table (2), is high compared to the proposed model.

The performance of the proposed model and BS 5400 provisions are compared with existing test outcomes is given in Figs. (3) and (4), respectively. The comparison of the test to predicted results, for the proposed model versus BS 5400 results, is given in Fig. (5). As shown in these figures, the correlation coefficient R2 is equal to 0.965 and 0.943 for the proposed model and BS 5400 code, respectively. These values indicate that a good agreement between the anticipation of the proposed model and the actual test values is achieved. The outcomes of the proposed model are found to be more suitable and accurate than the predictions of the BS 5400 design code. The proposed model is valid for all ranges of variables shown in Table (1).

**Table (2) Comparison between predicted and test patch loads**

| No. | $a$ (mm) | $b_1$ (mm) | $b_f$ (mm) | $f_{yf}$ (MPa) | $f_{yw}$ (MPa) | $h_w$ (mm) | $s_s$ (mm) | $t_f$ (mm) | $t_w$ (mm) | $F_{test}$ (kN) | Predicted load $F_s$ (kN) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Proposed | | BS 5400 | |
| | | | | | | | | | | | $F_s$ | $\frac{F_{test}}{F_s}$ | $F_s$ | $\frac{F_{test}}{F_s}$ |
| 1 | 1000 | 125 | 225 | 355 | 392 | 700 | 200 | 20 | 5 | 507.4 | 472.9 | 1.073 | 289.9 | 1.75 |
| 2 | 1000 | 125 | 225 | 355 | 392 | 700 | 200 | 20 | 5 | 520.6 | 472.9 | 1.101 | 290.8 | 1.79 |
| 3 | 1000 | 75 | 225 | 355 | 392 | 700 | 200 | 20 | 5 | 559.9 | 507.4 | 1.103 | 302.7 | 1.85 |
| 4 | 1000 | 100 | 225 | 355 | 392 | 700 | 200 | 20 | 5 | 582.1 | 487.9 | 1.193 | 297.0 | 1.96 |
| 5 | 1200 | 160 | 160 | 371 | 405 | 800 | 300 | 10 | 4 | 436.5 | 305.3 | 1.43 | 170.5 | 2.56 |
| 6 | 1200 | 300 | 200 | 364 | 447 | 800 | 300 | 15 | 6 | 632.1 | 581.0 | 1.088 | 361.2 | 1.75 |
| 7 | 1200 | 230 | 300 | 399 | 483 | 800 | 300 | 20 | 6 | 590.3 | 735.4 | 0.803 | 421.6 | 1.4 |
| 8 | 1800 | 160 | 300 | 399 | 483 | 800 | 300 | 20 | 6 | 698 | 757.2 | 0.922 | 447.4 | 1.56 |
| 9 | 1050 | 230 | 300 | 399 | 483 | 800 | 200 | 20 | 6 | 645.1 | 664.8 | 0.97 | 400.7 | 1.61 |
| 10 | 1050 | 160 | 300 | 399 | 483 | 800 | 200 | 20 | 6 | 777.9 | 702.4 | 1.107 | 422.8 | 1.84 |
| 11 | 2480 | 150 | 150 | 296 | 375 | 1000 | 40 | 8.35 | 3.8 | 130 | 176.7 | 0.736 | 111.1 | 1.17 |
| 12 | 1760 | 150 | 150 | 296 | 375 | 1000 | 40 | 8.35 | 3.8 | 176 | 178.9 | 0.984 | 115.8 | 1.52 |
| 13 | 1760 | 150 | 150 | 296 | 375 | 1000 | 40 | 8.35 | 3.8 | 172 | 178.9 | 0.961 | 115.4 | 1.49 |
| 14 | 2480 | 200 | 150 | 281 | 375 | 1000 | 40 | 8.35 | 3.8 | 135 | 171.6 | 0.787 | 108.0 | 1.25 |
| 15 | 1760 | 200 | 150 | 281 | 375 | 1000 | 40 | 8.35 | 3.8 | 165 | 173.7 | 0.95 | 112.2 | 1.471 |
| 16 | 1760 | 200 | 150 | 281 | 375 | 1000 | 40 | 8.35 | 3.8 | 170 | 173.7 | 0.979 | 112.6 | 1.51 |
| 17 | 2480 | 150 | 150 | 292 | 358 | 1000 | 240 | 8.3 | 3.8 | 160 | 239.9 | 0.667 | 124.0 | 1.29 |
| 18 | 1760 | 150 | 150 | 292 | 358 | 1000 | 240 | 8.3 | 3.8 | 280 | 242.4 | 1.155 | 132.7 | 2.11 |
| 19 | 1760 | 150 | 150 | 292 | 358 | 1000 | 240 | 8.3 | 3.8 | 300 | 242.4 | 1.238 | 132.7 | 2.261 |
| 20 | 2480 | 200 | 150 | 328 | 358 | 1000 | 240 | 8.3 | 3.8 | 199 | 231.5 | 0.86 | 116.4 | 1.71 |
| 21 | 1760 | 200 | 150 | 328 | 358 | 1000 | 240 | 8.3 | 3.8 | 229 | 233.6 | 0.98 | 128.7 | 1.779 |
| 22 | 1760 | 200 | 150 | 328 | 358 | 1000 | 240 | 8.3 | 3.8 | 235 | 233.6 | 1.006 | 129.1 | 1.82 |
| 23 | 2480 | 150 | 150 | 286 | 371 | 1000 | 40 | 12 | 3.8 | 130 | 192.5 | 0.675 | 132.7 | 0.98 |
| 24 | 1760 | 150 | 150 | 286 | 371 | 1000 | 40 | 12 | 3.8 | 198 | 195.0 | 1.015 | 135.6 | 1.46 |
| 25 | 1760 | 150 | 150 | 286 | 371 | 1000 | 40 | 12 | 3.8 | 210 | 195.0 | 1.077 | 135.5 | 1.55 |
| 26 | 2480 | 150 | 150 | 283 | 371 | 1000 | 40 | 12 | 3.8 | 145 | 192.6 | 0.753 | 131.8 | 1.1 |
| 27 | 1760 | 150 | 150 | 283 | 371 | 1000 | 40 | 12 | 3.8 | 184 | 195.1 | 0.943 | 136.3 | 1.35 |
| 28 | 1760 | 150 | 150 | 283 | 371 | 1000 | 40 | 12 | 3.8 | 180 | 195.1 | 0.923 | 136.4 | 1.32 |
| 29 | 2480 | 150 | 150 | 282 | 380 | 1000 | 240 | 12 | 3.8 | 247 | 271.2 | 0.911 | 138.0 | 1.79 |
| 30 | 1760 | 150 | 150 | 282 | 380 | 1000 | 240 | 12 | 3.8 | 330 | 274.1 | 1.204 | 152.1 | 2.17 |
| 31 | 1760 | 150 | 150 | 282 | 380 | 1000 | 240 | 12 | 3.8 | 315 | 274.1 | 1.149 | 152.2 | 2.07 |
| 32 | 2480 | 150 | 150 | 275 | 380 | 1000 | 240 | 12 | 3.8 | 161 | 271.6 | 0.593 | 141.2 | 1.14 |
| 33 | 1760 | 150 | 150 | 275 | 380 | 1000 | 240 | 12 | 3.8 | 275 | 274.5 | 1.002 | 151.9 | 1.81 |
| 34 | 1760 | 150 | 150 | 275 | 380 | 1000 | 240 | 12 | 3.8 | 288 | 274.5 | 1.049 | 151.6 | 1.9 |
| 35 | 3000 | 250 | 250 | 277 | 252 | 735 | 40 | 12 | 3 | 93.3 | 97.4 | 0.958 | 69.6 | 1.341 |
| 36 | 1100 | 250 | 250 | 277 | 252 | 735 | 40 | 12 | 3 | 92.4 | 100.1 | 0.923 | 69.5 | 1.329 |
| 37 | 1100 | 250 | 250 | 277 | 252 | 735 | 120 | 12 | 3 | 101 | 115.9 | 0.871 | 72.1 | 1.401 |
| 38 | 3000 | 150 | 250 | 277 | 252 | 735 | 40 | 12 | 3 | 104.7 | 104.2 | 1.005 | 75.9 | 1.379 |
| 39 | 1100 | 150 | 250 | 277 | 252 | 735 | 40 | 12 | 3 | 101.8 | 107.6 | 0.946 | 76.0 | 1.339 |
| 40 | 1100 | 150 | 250 | 277 | 252 | 735 | 120 | 12 | 3 | 106.3 | 123.7 | 0.859 | 78.7 | 1.351 |
| 41 | 505 | 250 | 50 | 439 | 236 | 505 | 50 | 5 | 2 | 30 | 30.3 | 0.99 | 24.0 | 1.25 |
| 42 | 505 | 250 | 50 | 439 | 239 | 505 | 50 | 5 | 2 | 35 | 30.7 | 1.14 | 24.1 | 1.452 |

Table (2) Continued

| **No.** | $a$ **(mm)** | $b_1$ **(mm)** | $b_f$ **(mm)** | $f_{yf}$ **(MPa)** | $f_{yw}$ **(MPa)** | $h_w$ **(mm)** | $s_s$ **(mm)** | $t_f$ **(mm)** | $t_w$ **(mm)** | $F_{test}$ **(kN)** | **Predicted load $F_s$ (kN)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | **Proposed** | | **BS 5400** | |
| | | | | | | | | | | | $F_s$ | $\frac{F_{test}}{F_s}$ | $F_s$ | $\frac{F_{test}}{F_s}$ |
| 43 | 505 | 250 | 50 | 453 | 231 | 505 | 50 | 5 | 2 | 33.5 | 29.5 | 1.136 | 23.8 | 1.408 |
| 44 | 505 | 100 | 50 | 453 | 234 | 505 | 50 | 5 | 2 | 36.5 | 35.8 | 1.02 | 27.2 | 1.342 |
| 45 | 505 | 100 | 50 | 446 | 232 | 505 | 50 | 5 | 2 | 35.6 | 35.6 | 1 | 27.2 | 1.309 |
| 46 | 505 | 100 | 50 | 458 | 233 | 505 | 50 | 5 | 2 | 41 | 35.6 | 1.152 | 27.2 | 1.507 |
| 47 | 505 | 50 | 50 | 485 | 236 | 505 | 50 | 5 | 2 | 35 | 40.2 | 0.871 | 28.9 | 1.211 |
| 48 | 505 | 50 | 50 | 466 | 234 | 505 | 50 | 5 | 2 | 42 | 40.1 | 1.047 | 29.0 | 1.448 |
| 49 | 505 | 50 | 50 | 467 | 239 | 505 | 50 | 5 | 2 | 39 | 40.8 | 0.956 | 29.1 | 1.34 |
| 50 | 505 | 50 | 50 | 471 | 232 | 505 | 50 | 5 | 2 | 42 | 39.8 | 1.055 | 28.8 | 1.458 |
| 51 | 505 | 50 | 50 | 461 | 231 | 505 | 50 | 5 | 2 | 47.5 | 39.7 | 1.196 | 28.6 | 1.661 |
| 52 | 505 | 50 | 50 | 481 | 233 | 505 | 50 | 5 | 2 | 42.5 | 39.8 | 1.068 | 28.7 | 1.481 |
| 53 | 1005 | 250 | 50 | 293 | 191 | 502.5 | 100 | 5 | 2 | 32 | 30.0 | 1.067 | 23.0 | 1.391 |
| 54 | 1005 | 250 | 50 | 472 | 210 | 502.5 | 100 | 5 | 2 | 34 | 30.9 | 1.1 | 24.1 | 1.411 |
| 55 | 1005 | 250 | 50 | 476 | 215 | 502.5 | 100 | 5 | 2 | 37.5 | 31.6 | 1.187 | 24.5 | 1.531 |
| 56 | 1005 | 100 | 50 | 295 | 204 | 502.5 | 100 | 5 | 2 | 32.5 | 37.1 | 0.876 | 27.1 | 1.199 |
| 57 | 1005 | 100 | 50 | 461 | 218 | 502.5 | 100 | 5 | 2 | 38 | 37.4 | 1.016 | 28.2 | 1.348 |
| 58 | 1005 | 100 | 50 | 470 | 218 | 502.5 | 100 | 5 | 2 | 38.2 | 37.4 | 1.021 | 28.1 | 1.359 |
| 59 | 1005 | 50 | 50 | 303 | 191 | 502.5 | 100 | 5 | 2 | 29 | 38.7 | 0.749 | 27.9 | 1.039 |
| 60 | 1005 | 50 | 50 | 293 | 204 | 502.5 | 100 | 5 | 2 | 33 | 41.0 | 0.805 | 29.0 | 1.138 |
| 61 | 1005 | 50 | 50 | 475 | 210 | 502.5 | 100 | 5 | 2 | 44 | 40.0 | 1.1 | 29.3 | 1.502 |
| 62 | 1005 | 50 | 50 | 469 | 218 | 502.5 | 100 | 5 | 2 | 34 | 41.3 | 0.823 | 29.8 | 1.141 |
| 63 | 1005 | 50 | 50 | 478 | 215 | 502.5 | 100 | 5 | 2 | 43 | 40.8 | 1.054 | 29.7 | 1.448 |
| 64 | 1005 | 50 | 50 | 473 | 218 | 502.5 | 100 | 5 | 2 | 40 | 41.3 | 0.969 | 29.9 | 1.338 |
| 65 | 622.5 | 200 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 315 | 261.1 | 1.206 | 211.4 | 1.49 |
| 66 | 622.5 | 200 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 300 | 261.1 | 1.149 | 211.3 | 1.42 |
| 67 | 622.5 | 125 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 342 | 308.4 | 1.109 | 234.3 | 1.46 |
| 68 | 622.5 | 125 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 327 | 308.4 | 1.06 | 233.6 | 1.4 |
| 69 | 622.5 | 75 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 370 | 359.9 | 1.028 | 248.3 | 1.49 |
| 70 | 622.5 | 75 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 395 | 359.9 | 1.098 | 248.4 | 1.59 |
| 71 | 622.5 | 200 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 285 | 261.1 | 1.092 | 211.1 | 1.35 |
| 72 | 622.5 | 200 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 295 | 261.1 | 1.13 | 210.7 | 1.4 |
| 73 | 622.5 | 125 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 290 | 308.4 | 0.94 | 233.9 | 1.24 |
| 74 | 622.5 | 125 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 299 | 308.4 | 0.97 | 233.6 | 1.28 |
| 75 | 622.5 | 75 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 351 | 359.9 | 0.975 | 248.9 | 1.41 |
| 76 | 622.5 | 75 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 338 | 359.9 | 0.939 | 248.5 | 1.36 |
| 77 | 622.5 | 200 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 296 | 261.1 | 1.134 | 211.4 | 1.4 |
| 78 | 622.5 | 200 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 276 | 261.1 | 1.057 | 210.7 | 1.31 |
| 79 | 622.5 | 125 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 300 | 308.4 | 0.973 | 234.4 | 1.28 |
| 80 | 622.5 | 125 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 282 | 308.4 | 0.914 | 233.1 | 1.21 |
| 81 | 622.5 | 75 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 372 | 359.9 | 1.034 | 248.0 | 1.5 |
| 82 | 622.5 | 75 | 120 | 242 | 256 | 500 | 62 | 12 | 6 | 399 | 359.9 | 1.109 | 247.8 | 1.61 |
| 83 | 500 | 100 | 100 | 292 | 224 | 500 | 50 | 5.1 | 2.4 | 40 | 48.7 | 0.821 | 36.0 | 1.111 |
| 84 | 500 | 100 | 119.9 | 309 | 238 | 500 | 50 | 6.1 | 2.2 | 55 | 49.0 | 1.122 | 34.6 | 1.59 |
| 85 | 500 | 100 | 119.8 | 309 | 238 | 500 | 50 | 6 | 2.2 | 57.5 | 48.7 | 1.181 | 34.4 | 1.672 |
| 86 | 500 | 100 | 120.2 | 309 | 238 | 500 | 50 | 6 | 2.2 | 62 | 48.7 | 1.273 | 34.4 | 1.802 |
| 87 | 500 | 100 | 119.9 | 239 | 238 | 500 | 50 | 11.7 | 2.2 | 65 | 66.7 | 0.975 | 46.1 | 1.41 |
| 88 | 500 | 100 | 119.3 | 239 | 238 | 500 | 50 | 11.9 | 2.2 | 66.5 | 67.3 | 0.988 | 46.5 | 1.43 |
| 89 | 500 | 100 | 119.7 | 239 | 238 | 500 | 50 | 11.9 | 2.2 | 59 | 67.3 | 0.877 | 46.5 | 1.269 |
| 90 | 500 | 100 | 118.6 | 262 | 362 | 500 | 50 | 8.5 | 4.4 | 192 | 219.3 | 0.876 | 148.8 | 1.29 |
| 91 | 500 | 100 | 119.3 | 262 | 360 | 500 | 50 | 8.4 | 4 | 190 | 186.6 | 1.018 | 125.8 | 1.51 |
| 92 | 500 | 100 | 119.1 | 262 | 360 | 500 | 50 | 7.8 | 4 | 202 | 181.5 | 1.113 | 123.2 | 1.64 |
| 93 | 500 | 100 | 119.2 | 262 | 360 | 500 | 50 | 8.5 | 4 | 193.5 | 187.4 | 1.033 | 126.5 | 1.53 |
| 94 | 500 | 100 | 120.9 | 285 | 360 | 500 | 50 | 20 | 4 | 315 | 274.3 | 1.148 | 182.1 | 1.73 |
| 95 | 500 | 100 | 120.6 | 285 | 360 | 500 | 50 | 20 | 4 | 290 | 274.2 | 1.058 | 305.3 | 0.95 |
| 96 | 500 | 100 | 120.4 | 285 | 360 | 500 | 50 | 20 | 4 | 276 | 274.2 | 1.007 | 306.7 | 0.9 |
| 97 | 500 | 100 | 120.2 | 239 | 426 | 500 | 50 | 11.9 | 5.6 | 339 | 428.4 | 0.791 | 271.2 | 1.25 |
| 98 | 500 | 100 | 89.7 | 277 | 426 | 500 | 50 | 12.3 | 5.6 | 387 | 415.5 | 0.931 | 272.5 | 1.42 |
| 99 | 500 | 100 | 89.7 | 277 | 455 | 500 | 50 | 12.3 | 5.5 | 408 | 421.5 | 0.968 | 273.8 | 1.49 |
| 100 | 500 | 100 | 89.4 | 277 | 455 | 500 | 50 | 12.1 | 5.5 | 420 | 418.7 | 1.003 | 272.7 | 1.54 |
| 101 | 500 | 100 | 99 | 254 | 426 | 500 | 50 | 30.4 | 5.6 | 564 | 641.0 | 0.88 | 402.9 | 1.4 |
| 102 | 500 | 100 | 100 | 254 | 426 | 500 | 50 | 30.5 | 5.6 | 592 | 642.9 | 0.921 | 402.7 | 1.47 |
| 103 | 500 | 100 | 100.1 | 254 | 426 | 500 | 50 | 30 | 5.6 | 610 | 637.4 | 0.957 | 401.3 | 1.52 |
| 104 | 500 | 100 | 119.6 | 274 | 244 | 500 | 50 | 6 | 2 | 55 | 44.1 | 1.247 | 29.9 | 1.839 |
| 105 | 500 | 100 | 119.9 | 274 | 244 | 500 | 50 | 6 | 2 | 50 | 44.1 | 1.134 | 29.9 | 1.672 |

Table (2) Continued

| No. | $a$ (mm) | $b_1$ (mm) | $b_f$ (mm) | $f_{yf}$ (MPa) | $f_{yw}$ (MPa) | $h_w$ (mm) | $s_s$ (mm) | $t_f$ (mm) | $t_w$ (mm) | $F_{test}$ (kN) | Predicted load $F_s$ (kN) Proposed $F_s$ | Proposed $\frac{F_{test}}{F_s}$ | BS 5400 $F_s$ | BS 5400 $\frac{F_{test}}{F_s}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 106 | 500 | 100 | 119.9 | 274 | 244 | 500 | 50 | 6.1 | 2 | 57 | 44.4 | 1.284 | 30.2 | 1.887 |
| 107 | 500 | 100 | 120.7 | 254 | 244 | 500 | 50 | 12.1 | 2 | 84 | 61.0 | 1.377 | 41.0 | 2.049 |
| 108 | 500 | 100 | 120.7 | 254 | 244 | 500 | 50 | 12.1 | 2 | 72 | 61.0 | 1.18 | 40.9 | 1.76 |
| 109 | 500 | 100 | 120.8 | 254 | 244 | 500 | 50 | 12.1 | 2 | 76 | 61.0 | 1.246 | 40.9 | 1.858 |
| 110 | 500 | 100 | 120.1 | 294 | 283 | 500 | 50 | 8.4 | 4 | 171 | 152.9 | 1.118 | 111.8 | 1.53 |
| 111 | 500 | 100 | 120.2 | 294 | 283 | 500 | 50 | 8.5 | 4 | 156 | 153.7 | 1.015 | 112.2 | 1.39 |
| 112 | 500 | 100 | 120.4 | 294 | 283 | 500 | 50 | 8.3 | 4 | 185 | 152.1 | 1.216 | 111.5 | 1.659 |
| 113 | 500 | 100 | 120.9 | 270 | 283 | 500 | 50 | 20.3 | 4 | 256.5 | 240.6 | 1.066 | 162.3 | 1.58 |
| 114 | 500 | 100 | 120.9 | 270 | 283 | 500 | 50 | 20.4 | 4 | 248 | 241.3 | 1.028 | 163.2 | 1.52 |
| 115 | 500 | 100 | 120.7 | 270 | 283 | 500 | 50 | 20.2 | 4 | 257 | 239.9 | 1.071 | 162.7 | 1.58 |
| 116 | 500 | 100 | 90.7 | 272 | 396 | 500 | 50 | 12.4 | 5.4 | 336 | 374.0 | 0.898 | 248.9 | 1.35 |
| 117 | 500 | 100 | 90.8 | 272 | 396 | 500 | 50 | 12.3 | 5.4 | 387.5 | 372.8 | 1.039 | 248.4 | 1.56 |
| 118 | 500 | 100 | 90.7 | 272 | 396 | 500 | 50 | 12.4 | 5.4 | 399 | 374.0 | 1.067 | 249.4 | 1.6 |
| 119 | 500 | 100 | 99.6 | 269 | 396 | 500 | 50 | 30.4 | 5.4 | 610 | 577.1 | 1.057 | 367.5 | 1.66 |
| 120 | 500 | 100 | 99.3 | 269 | 396 | 500 | 50 | 30.6 | 5.4 | 600 | 579.0 | 1.036 | 368.1 | 1.63 |
| 121 | 500 | 100 | 100.2 | 269 | 396 | 500 | 50 | 30.6 | 5.4 | 605 | 579.7 | 1.044 | 368.9 | 1.64 |
| 122 | 500 | 50 | 120.3 | 278 | 304 | 500 | 50 | 8.3 | 4.1 | 201 | 197.9 | 1.016 | 128.0 | 1.57 |
| 123 | 500 | 50 | 120.4 | 278 | 304 | 500 | 50 | 8.3 | 4.1 | 196 | 197.9 | 0.99 | 127.3 | 1.54 |
| 124 | 500 | 50 | 120.8 | 278 | 304 | 500 | 50 | 8.2 | 4.1 | 186 | 197.1 | 0.944 | 127.4 | 1.46 |
| 125 | 500 | 50 | 120.6 | 278 | 304 | 500 | 50 | 8.1 | 4.1 | 199 | 196.2 | 1.014 | 126.8 | 1.569 |
| 126 | 500 | 50 | 120.3 | 278 | 304 | 500 | 50 | 8.2 | 4.1 | 199 | 197.0 | 1.01 | 126.8 | 1.569 |
| 127 | 500 | 50 | 120.8 | 278 | 304 | 500 | 50 | 8.2 | 4.1 | 186 | 197.1 | 0.944 | 127.4 | 1.46 |
| 128 | 500 | 50 | 120.7 | 278 | 304 | 500 | 50 | 8.1 | 4.1 | 187 | 196.2 | 0.953 | 126.4 | 1.479 |
| 129 | 500 | 50 | 120.6 | 278 | 304 | 500 | 50 | 8.4 | 4.1 | 210 | 198.8 | 1.056 | 128.1 | 1.639 |
| 130 | 500 | 50 | 120.7 | 278 | 304 | 500 | 50 | 8.1 | 4.1 | 192 | 196.2 | 0.979 | 126.3 | 1.52 |
| 131 | 500 | 50 | 120.7 | 278 | 304 | 500 | 50 | 8.2 | 4.1 | 208 | 197.1 | 1.055 | 126.8 | 1.64 |
| 132 | 500 | 50 | 118.2 | 244 | 304 | 500 | 50 | 19.7 | 4.1 | 243 | 290.5 | 0.836 | 182.7 | 1.33 |
| 133 | 500 | 50 | 118.6 | 244 | 304 | 500 | 50 | 19.7 | 4.1 | 237 | 290.6 | 0.816 | 183.7 | 1.29 |
| 134 | 500 | 50 | 118.5 | 244 | 304 | 500 | 50 | 19.8 | 4.1 | 267 | 291.3 | 0.917 | 184.1 | 1.45 |
| 135 | 500 | 50 | 118.4 | 244 | 304 | 500 | 50 | 19.9 | 4.1 | 259 | 292.0 | 0.887 | 183.7 | 1.41 |
| 136 | 500 | 50 | 118.6 | 244 | 304 | 500 | 50 | 19.8 | 4.1 | 255 | 291.4 | 0.875 | 183.5 | 1.39 |
| 137 | 500 | 50 | 118.7 | 244 | 304 | 500 | 50 | 19.9 | 4.1 | 261 | 292.1 | 0.894 | 183.8 | 1.42 |
| 138 | 500 | 50 | 118.6 | 244 | 304 | 500 | 50 | 19.7 | 4.1 | 264 | 290.6 | 0.908 | 183.3 | 1.44 |
| 139 | 500 | 50 | 118.3 | 244 | 304 | 500 | 50 | 19.6 | 4.1 | 266 | 289.8 | 0.918 | 182.2 | 1.46 |
| 140 | 500 | 50 | 118.3 | 244 | 304 | 500 | 50 | 19.6 | 4.1 | 270 | 289.8 | 0.932 | 182.4 | 1.48 |
| 141 | 500 | 50 | 118.4 | 244 | 304 | 500 | 50 | 19.6 | 4.1 | 285 | 289.8 | 0.983 | 182.7 | 1.56 |
| 142 | 802 | 168 | 300.5 | 286 | 266 | 798 | 40 | 15.55 | 2.1 | 71 | 92.3 | 0.769 | 51.1 | 1.389 |
| 143 | 800 | 162 | 120.4 | 285 | 266 | 798 | 40 | 5.07 | 2 | 45 | 48.2 | 0.934 | 28.1 | 1.601 |
| 144 | 800 | 168 | 300 | 295 | 266 | 800 | 40 | 15 | 2 | 68.5 | 86.1 | 0.796 | 46.6 | 1.47 |
| 145 | 800 | 162 | 120 | 285 | 266 | 800 | 40 | 5 | 2 | 42.5 | 48.2 | 0.882 | 28.0 | 1.518 |
| 146 | 2500 | 160 | 300 | 295 | 300 | 800 | 40 | 15 | 2 | 80 | 89.6 | 0.893 | 50.0 | 1.6 |
| 147 | 1200 | 160 | 300 | 295 | 300 | 800 | 40 | 15 | 2 | 78 | 91.0 | 0.857 | 50.0 | 1.56 |
| 148 | 600 | 160 | 300 | 295 | 300 | 800 | 40 | 15 | 2 | 92 | 96.2 | 0.956 | 50.0 | 1.84 |
| 149 | 2500 | 160 | 250 | 265 | 245 | 800 | 40 | 12 | 3 | 132.6 | 102.7 | 1.291 | 74.9 | 1.77 |
| 150 | 1200 | 160 | 250 | 265 | 245 | 800 | 40 | 12 | 3 | 97.5 | 105.5 | 0.924 | 75.0 | 1.3 |
| 151 | 600 | 160 | 250 | 265 | 245 | 800 | 40 | 12 | 3 | 121.4 | 115.9 | 1.047 | 74.9 | 1.621 |
| 152 | 2200 | 136 | 120 | 290 | 354 | 680 | 40 | 5 | 2 | 45.8 | 55.3 | 0.828 | 32.5 | 1.409 |
| 153 | 1020 | 136 | 120 | 290 | 354 | 680 | 40 | 5 | 2 | 54.4 | 56.4 | 0.965 | 32.4 | 1.679 |
| 154 | 510 | 136 | 120 | 290 | 354 | 680 | 40 | 5 | 2 | 54.7 | 60.3 | 0.907 | 32.6 | 1.678 |
| 155 | 897.1 | 180 | 181.2 | 266 | 270 | 899.1 | 90 | 8 | 3.2 | 105.42 | 118.8 | 0.887 | 54.9 | 1.92 |
| 156 | 892.2 | 180 | 180.4 | 266 | 270 | 901.5 | 90 | 8 | 3.2 | 110.36 | 119.0 | 0.927 | 56.9 | 1.94 |
| 157 | 1780 | 327 | 230 | 244 | 279 | 1274 | 690 | 40 | 6 | 720 | 798.8 | 0.901 | 510.6 | 1.41 |
| 158 | 1780 | 264 | 230 | 267 | 286 | 1274 | 690 | 40 | 6 | 730 | 831.2 | 0.878 | 493.2 | 1.48 |
| 159 | 1000 | 200 | 300 | 235.2 | 325 | 1000 | 300 | 9 | 6 | 438.2 | 477.2 | 0.918 | 260.8 | 1.68 |
| 160 | 635 | 127 | 152.4 | 303 | 303 | 635 | 127 | 12.7 | 3.2 | 130 | 157.9 | 0.823 | 79.8 | 1.629 |
| 161 | 635 | 127 | 152.4 | 275 | 275 | 635 | 127 | 6.35 | 3.2 | 85 | 116.0 | 0.733 | 59.9 | 1.419 |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | **Average** | 0.996 | | 1.512 |
| | | | | | | | | | | | **Standard deviation** | 0.136 | | 0.243 |
| | | | | | | | | | | | **Coefficient of variation** | 13.65 | | 16.07 |

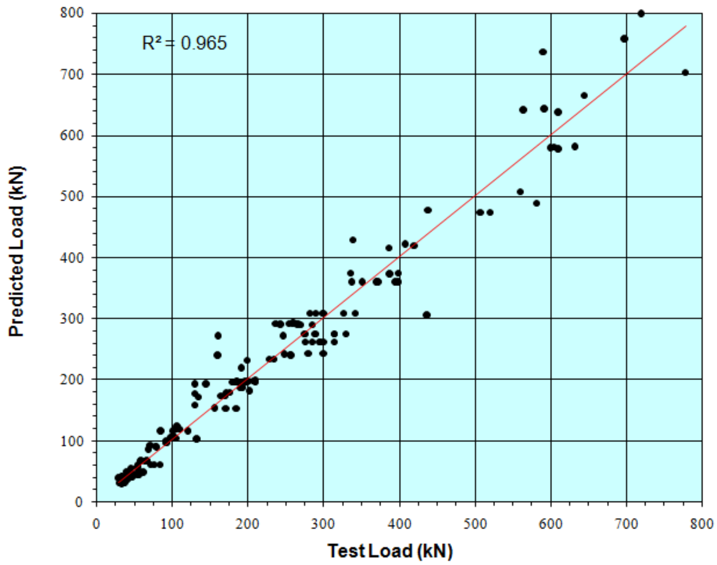



**Figure (3) Performance of the proposed model**

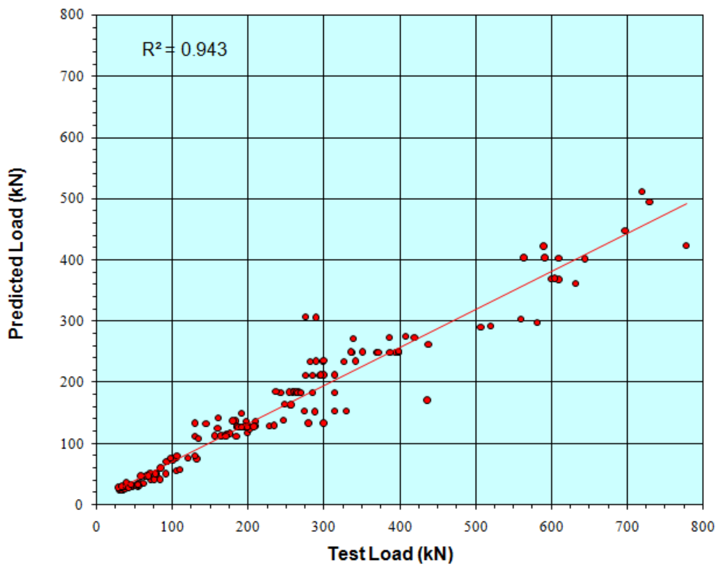



**Figure (4) Performance of the BS 5400 predictions**

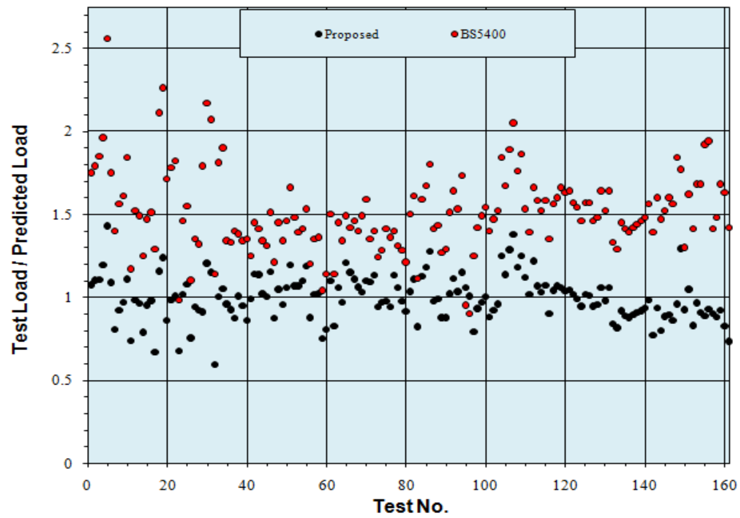
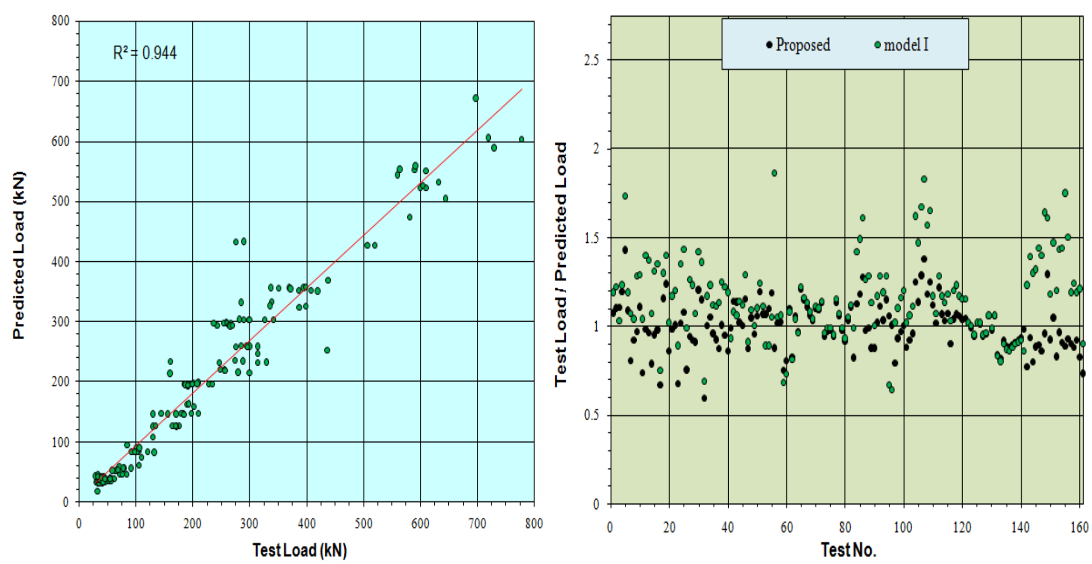



**Figure (5) Comparison of test to predicted ratios for the proposed model versus BS 5400 predictions**

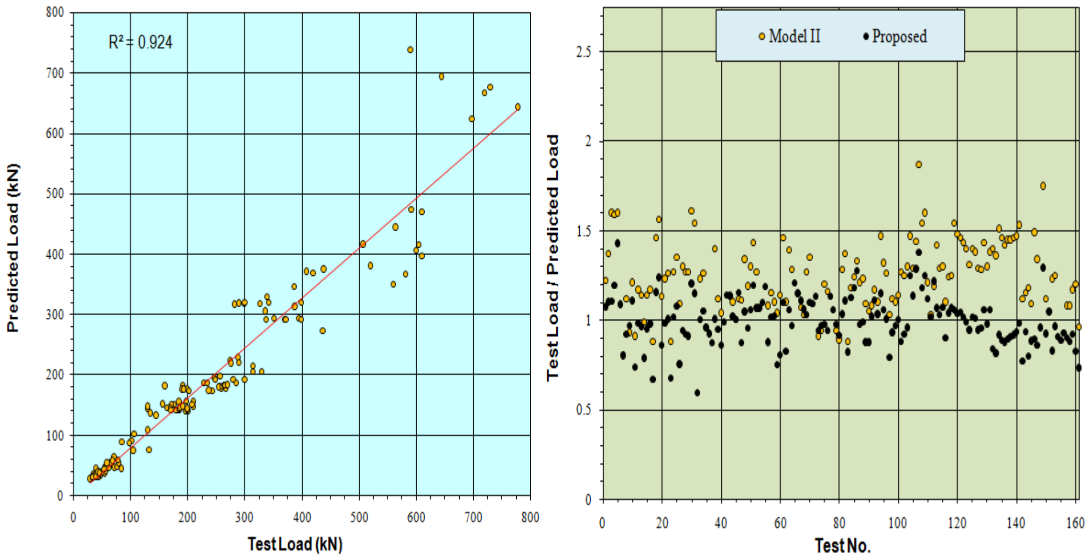
## 6. Comparison with Some Existing Models

The values of the patch load, for the used test data, estimated by the proposed model are compared with the results of two different existing models. The first model, model I, was proposed by Graciano and Edlund [9] who improved a failure mechanism model based on a yield line mechanism in order to include the effect of longitudinal stiffening. While the second one, model II, was presented by Graciano and Johansson [10] by proposing a model according to the design philosophy of the Eurocode3 Part 1.5 [16] based on the post-critical strength of the plate girders. The comparison of the results of the proposed model with the results of mode I and mode II is given in Figs. (6) and (7), respectively. As can be seen from these figures, R2 = 0.944 and 0.924 for model I and model II, respectively, while R2 = 0.965 for the proposed model (Fig. 3). These values indicate that the estimated results of the proposed model are more correct and accurate than the predictions of model I and model II.




(a) (b)

**Figure (6) Comparison between the proposed model and model I**




**(a)** **(b)**

**Figure (7) Comparison between the proposed model and model II**

## 7. Conclusions

Patch load modeling is generally mechanical or regression models based on the existing test outcomes. This study submits an alternative model for the determination of the ultimate patch load of plate girders that stiffened longitudinally. The proposed model consists of empirical equations based on a wide domain of existing test database from the open literature. The present proposed model shows a very good agreement with test results (R2= 0.965), and it is more quite accurate than the BS 5400 code predictions. The proposed model has significant advantages since it is adequate for the whole variables ranges that used in the database, where some previous patterns are not valid if specified ranges are exceeded.

**Conflicts of Interest**

The author declares that they have no conflicts of interest.

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# سعة تحمّل العوارض الصفيحية الحديدية المُصلَّبة

**احمد صكبان سعدون    عبدالناصر محمد عباس    علي عبدالحسن خلف**

*قسم الهندسة المدنية، كلية الهندسة، جامعة البصرة.*

ali_abd575@yahoo.com  nasser21272@gmail.com  ahmsag@gmail.com

**الخلاصة**

يهدف هذا البحث الى اقتراح نموذج بديل لتحديد الحمل الاقصى للعوارض الصفيحية المصلبة طولياً. استند النموذج المقترح على المعادلات وضعية وتحليل الانحدار وقد أُكِّدَت نتائجه مع قاعدة بيانات لِعديد من النتائج المختبرية السابقة والمتوفرة. وتمت المقارنة بين النتائج المستحصلة من النموذج المقترح مع النتائج المستحصلة من استخدام المواصفات البريطانية (BS 5400). ولقد وُجِدَ بأن النموذج المقترح يعطي نتائج متوافقة جداً مع النتائج المختبرية وأعلى دِقَّة مما تعطيه المواصفات البريطانية.

**كلمات الدالة:** عوارض صفيحية، عوارض مُصلَّبة، سعة التحمل، تحليل الانحدار.