Journal of the Civil Engineering Forum, September 2022, 8(3): 291-300
DOI 10.22146/jcef.3416
Available Online at: https://journal.ugm.ac.id/v3/JCEF/issue/archive

Increasing the Inventory Rating Factor of Steel Truss Bridge Through Orthotropic Steel Deck Panel Application

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SUBMITTED 17 September 2021 **REVISED** 4 March 2022 **ACCEPTED** 9 June 2022

ABSTRACT Currently, 18,648 bridges with a total length of 510,366 km have been constructed in Indonesia, but only 86% are in good condition, while the rest are damaged. Steel truss bridge damage generally occurs on the RC decks, and its repair is often implemented through deck replacement or redecking using Orthotropic Steel Deck (OSD) panel. In Indonesia, this method has only been applied limitedly at the Citarum I Bridge in 2009 and the Cisadane Bridge in 2013, while the effect on the existing steel truss bridge is unknown. Therefore, this study aims to evaluate the steel truss bridge performance after OSD panel redecking through numerical modeling. The design process of the OSD panel was carried out by micro-modeling on ABAQUS CAE using shell elements with a mesh size of 50x50 mm and pinned boundary conditions. In this stage, the materials were assumed to be elastic with small deformations. The evaluation of steel truss bridge performance was performed on the A-class steel truss bridge Bina Marga design standard with a 60 m span by comparing the existing bridge inventory rating factor (using RC decks) to OSD panel redecking, which is an indicator of bridge self-weight reduction. Based on the structural macro-model developed using SAP2000, the bridge self-weight reduced the axial tension and compression forces on the steel truss bridge mainframe by 20.6%-24.6% and 20.5%-24.5%, respectively. Consequently, this increased the inventory rating factor by 9.3%-9.5%. In other words, using the OSD panels lighter than the existing RC decks increases the steel truss bridge capacity to resist the live load or vehicle rating throughout its service life.

KEYWORDS Redecking; Orthotropic Steel Deck Panel; Steel Truss Bridge; Inventory Rating Factor.

1 INTRODUCTION

In the last decade, Indonesia has achieved massive infrastructure developments including airports, ports, MRT, LRT, toll roads, and bridges. There are currently 18,648 bridges with a total length of 510,366 km (Ministry of Public Works and Public Housing, 2020). These include prestressed concrete girder, steel truss, continuous concrete and steel, concrete arch, steel arch, cable-stayed, and suspension bridge (Dewobroto *et al.,* 2014; Sukmana and Vaza, 2016; Directorate General of Highways, 2021). From 1970 to 1990, steel truss bridges were used in most construction projects in Indonesia (Dewobroto *et al.,* 2014). Some bridges were also imported from several countries such as England (Callendar Hamilton and Compact Bailey), Netherland (Hollandia Kloos), and Australia (Transfield and Trans Bakrie) (Dewobroto *et al.,* 2014).

Several bridges in Indonesia are now over 50 years old, indicating that they are experiencing structural deterioration due to aging (Imran *et al.,* 2014). Approximately 86% of all bridges are in good condition, while the rest are damaged (Ministry of Public Works and Public Housing, 2020). Bridge deterioration is caused by a wet, hot, humid climate (Oktavianus *et al.,* 2020). It can also be caused by overloading, as well as foundation, structural, and bridge floor damage

(Soetjipto *et al.,* 2017). Generally, steel truss bridge damage occurs on the RC decks (Road and Bridge Research & Development Center, 2017), which is repaired by bridge access closure. This has potentially enormous consequences because bridges are an essential part of the transportation system (Moehle and Eberhard, 2000). RC decks can be repaired through deck replacement or redecking using Orthotropic Steel Deck (OSD). The OSD panel prefabricated in the workshop can be quickly constructed in the field, thereby shortening the bridge closure duration.

OSD was first developed by German engineers in the 1930s. It has a low self-weight and slender structure, reducing stress and providing an aesthetic impression on the bridge (Karlsson, 2014; Håkansson and Wallerman, 2015). The word *orthotropic* is taken from the *ortho* for *orthogonal* and *tropic* for *anisotropic* (Mangus and Sun, 2000). OSD consists of steel plates stiffened by longitudinal ribs and orthogonal transverse floor beams. Hence, it has different stiffness in the longitudinal and transverse directions (Connor *et al.,* 2012). RC decks repair through OSD redecking has been widely used, such as Lions Gate Bridge (Canada), George Washington Bridge (USA), Golden Gate Bridge (USA), Throngs Neck Bridge (USA), Benjamin Franklin Bridge (USA), Champlain Bridge (Canada), Bronx-Whitestone Bridge (USA), Verrazano Bridge (USA), Walt Whitman Bridge (USA), Macdonald Bridge (Canda), and Broadway Bridge (US) (Mangus and Sun, 2000; Tsakopoulos and Fisher, 2005; Wolchuk, 2014; Pipinato, 2016). This is due to advantages which include lightweight, *rapid erection*, easy assembly and maintenance, suitable for standardization and prefabrication, support the acceleration of bridge construction, reduce traffic disruption, improve work zone safety, and low life-cycle costs (Connor *et al.,* 2012; Ocel *et al.,* 2017). In Indonesia, OSD redecking has only been applied limitedly at the Citarum I Bridge in 2009 and the Cisadane Bridge in 2013 (Road and Bridge Research & Development Center, 2017). Furthermore, its application on the steel truss bridge is presented in Figure 1. However, the effect of OSD panel redecking on the existing steel truss bridge is unknown. Most of the previous studies focused on fatigue performance (Zhang *et al.,* 2017; 2018; Luo *et al.,* 2019; Liu *et al.,* 2019a; Huang *et al.,* 2020b), OSD component optimization (Xu *et al.,* 2021; Laan, 2021; Huang *et al.,* 2020a), and the development of steel ultra-high performance concrete (steel-UHPC) composite deck (Yuan *et al.,* 2019; Liu *et al.,* 2019b; Wang *et al.,* 2021; Cheng *et al.,* 2021; Chen *et al.,* 2019; Shao *et al.,* 2018).

Figure 1. Bridge deck cross section (Road and Bridge Research & Development Center, 2017)

This study aims to evaluate the steel truss bridge performance based on OSD panel redecking. It was carried out on the A-class steel truss bridge Bina Marga design standard with 60 m spans (Directorate General of Highways, 2005). The evaluation was performed by comparing the existing bridge inventory rating factor (using RC decks) to OSD panel redecking.

2 METHODS

2.1 OSD Panel and Steel Truss Bridge Geometry

OSD panel installation was carried out with ribs parallel to the bridge traffic direction, as shown in Figure 2. The dimension was 1.7x5 m, as demonstrated in Figure 3. The OSD panel used trapezoidal ribs with a cross-section geometry, referring to the Manual for Design, Construction, and Maintainance of Orthotropic Steel Deck (Connor *et al.,* 2012). The steel used in plate, ribs, and floor beam OSD panel have yield stress, f_y = 240 MPa and ultimate stress, f_u = 370 MPa. This study extends from previous data on the effect of OSD panel redecking on the deck and bridge self-weight (Pradana and Triwiyono, 2017). In the previous study, the plates, ribs, and floor beams thickness of OSD panels were designed based on the variation of service life design comprising 10, 20, 30, 40, and 50 years, as well as average daily traffic of 1000, 2000, and 3000 trucks/day. The design process was carried out by micro-modeling on ABAQUS CAE using shell elements with a mesh size of 50x50 mm and pinned boundary conditions. In this stage, the materials were assumed to be elastic with small deformations.

The considered design loads include the self-weight, pavement, and vehicular live load HL-93 (American Association of State Highway and Transportation Officials, 2012). OSD panel stresses were evaluated to strength, service, and fatigue limit states according to AASHTO LRFD Bridge Design Specifications 2012 (American Association of State Highway and Transportation Officials, 2012). Next, the design was applied as a repair method for the steel truss bridge to replace RC decks. The procedures were carried out on the A-class steel truss bridge Bina Marga design standard with 60 m spans, as shown in Figure 4 (Directorate General of Highways, 2005).

The redecking effect on the distribution of the main internal frame forces was evaluated by macro-modeling using SAP2000. The considered design loads include the self-weight, pavement, rainwater puddles, curbs, lane loads (D), and truckloads (T) (National Standardization Agency, 2005). Meanwhile, the redecking effect on the steel truss bridge performance was evaluated using the inventory rating factor, the available capacity to resist the live load compared to a specific live load working on the bridge (Directorate General of Highways, 2011).

2.2 Rating Factor Calculation

Bridge structure capacity can be evaluated using the rating factor, which is the available capacity to resist the live load compared to the vehicle rating (Directorate General of Highways, 2011). Rating factors are divided into two, namely inventory and operating. The inventory rating factor considers the design or a specific daily load that can be resisted by the bridge structure throughout its service life. In contrast, the operating rating factor considers the maximum load allowed to work on the bridge structure.

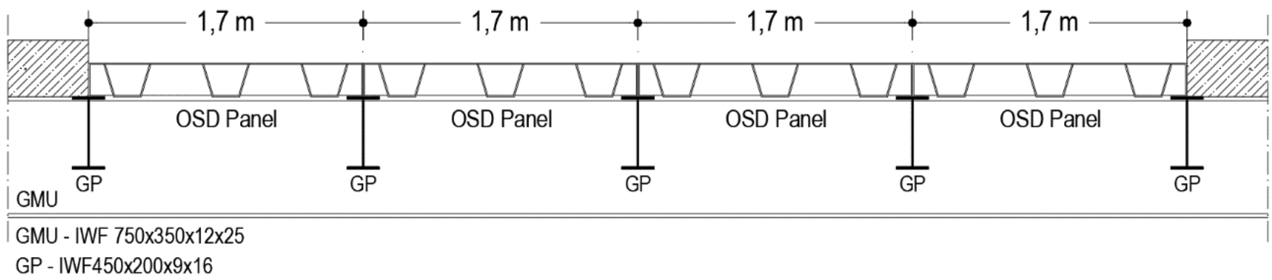


Figure 2. Bridge deck cross-section

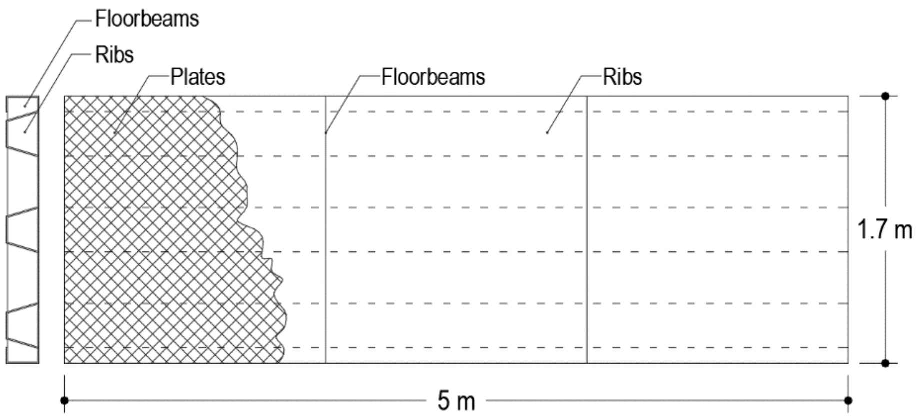


Figure 3. OSD Panel Geometry (Pradana and Triwiyono, 2017)

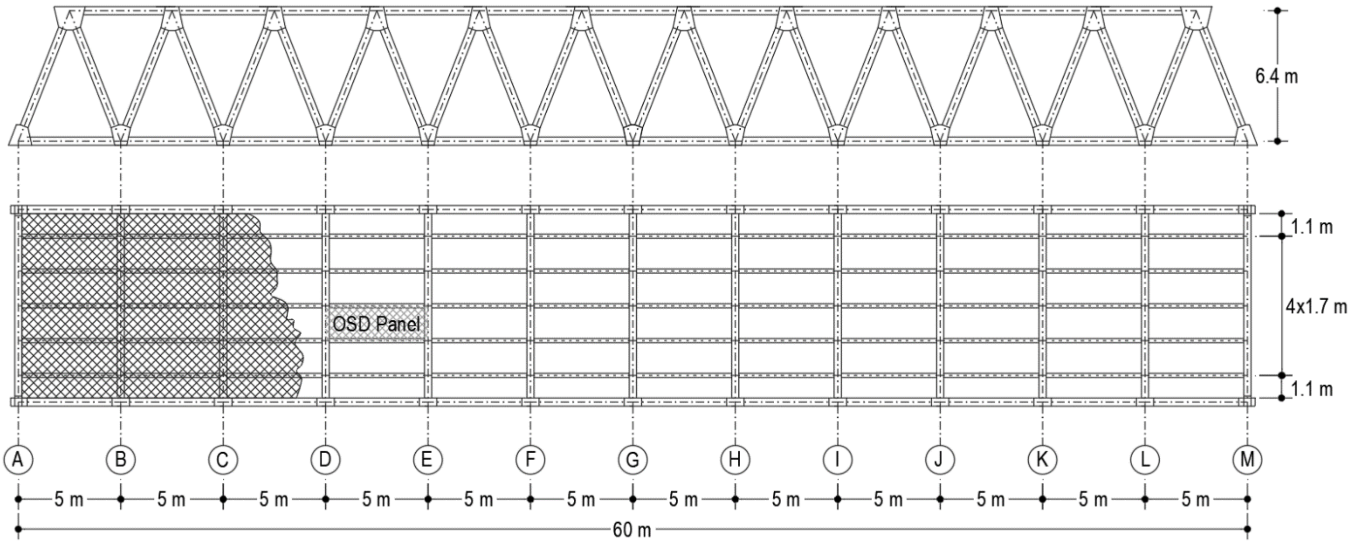


Figure 4. The A-Class Steel Truss Bridge Bina Marga Design Standard with 60 m Spans (Directorate General of Highways, 2005)

The rating factor value can be calculated using Equation (1) (Directorate General of Highways, 2011), where RF is the rating factor; Ø is the strength reduction factor (taken by 0.9 for tension; 0.85 for compression; and 0.9 for bending); R_n is the nominal capacity of the structural element; DL is the internal forces due to dead load; LL is the internal forces due to live load according to RSNI T-02-2005; γ_D is the dead load factor (1,30); γ_L is the live load factor (taken by 2.17 for inventory rating factor and 1.30 for operating rating factor); and I is the impact factor.

$$RF = \frac{\emptyset R_n - \Sigma(\gamma_D . DL)}{\gamma_L \, . \, LL\,(1 + I)} \tag{1}$$

A rating factor value greater than 1.0 indicates that the bridge structure can support the working live load. If the rating factor value increases, the steel truss bridge capacity to resist the live load or vehicle rating throughout its service life will also be increased. Therefore, this value can be used to evaluate the OSD panel redecking effect on steel truss bridge performance.

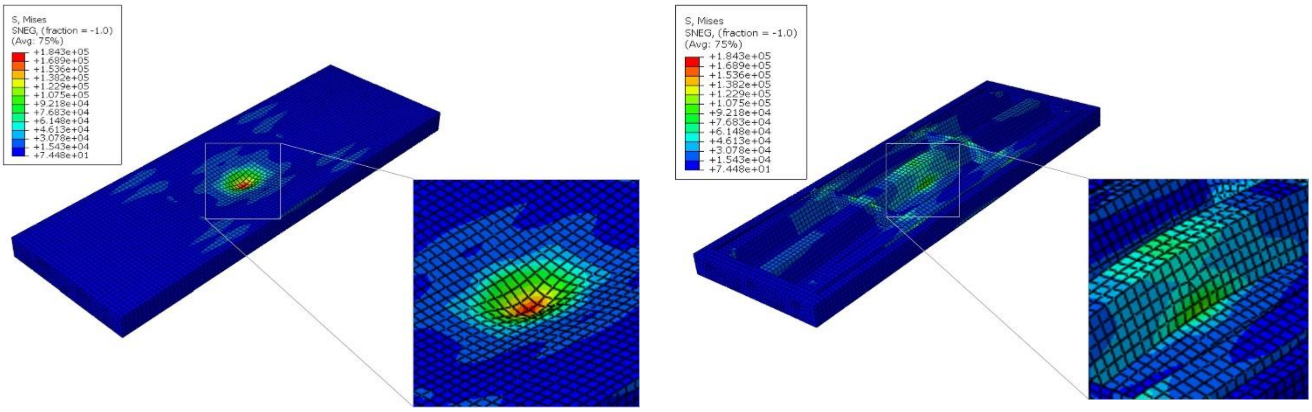
3 RESULT AND DISCUSSION

3.1 Design of Ribs-Floorbeams-Plates OSD and Deck Panel Weight Reduction

The structural model of the OSD panel was developed using ABAQUS CAE. Figures 5a and 5b present the maximum Von Mises stress contours on the top and bottom surfaces of the OSD panel, which were evaluated to strength, service, and fatigue limit states, respectively (American Association of State Highway and Transportation Officials, 2012). Based on the structural model, the maximum Von Mises stress of OSD panel on the top surface occurs at plates (see Figure 5a), while on the bottom surface, it occurs at ribs (see Figure 5b).

This study extends from a previous investigation that evaluated the OSD panel redecking effect on the deck and bridge self-weight (Pradana and Triwiyono, 2017). In the previous study, plates, ribs, and floor beams thickness were designed based on the variation of service life design comprising 10, 20, 30, 40, and 50 years, as well as the average daily traffic of 1000, 2000, and 3000 trucks/day, as presented in Table 1.

The OSD panel redecking reduced the deck weight by 19.8%-42.2% and the bridge self-weight by 9.6%-20.6% (Pradana and Triwiyono, 2017). This is consistent with several previous studies, which stated that the OSD application could reduce the self-weight of the structure by approximately 18%-25% (Mangus and Sun, 2000; Yang *et al.*, 2018). Furthermore, the OSD panel redecking effect on the internal forces and the steel truss bridge performance were also evaluated.



(a) (b)

Figure 5. The Maximum Von Mises Stress Contours on the: (a) Top and (b) Bottom Surfaces of OSD Panel (Pradana and Triwiyono, 2017)

Table 1. Steel Thickness Design of OSD Panel (Pradana and Triwiyono, 2017)

Notation	Service Life Design of OSD (years)	Average Daily Traffic (truck/ day)	Thickness Component			OSD Panel Weight 1.7x5 m (kN)	RC Deck Panel Weight 1.7x5 m (kN)	Weight Reduction per Panel (%)
			Ribs (mm)	Floor-beams (mm)	Plates (mm)			
Design A1	10		16	16	20	32.7	52.0	37.06
Design A2	20		16	16	24	35.4	52.0	31.92
Design A3	30	3000	16	16	26	36.7	52.0	29.36
Design A4	40		16	16	28	38.1	52.0	26.79
Design A5	50		19	19	28	41.7	52.0	19.80
Design B1	10		16	16	18	31.4	52.0	39.62
Design B2	20		16	16	22	34.1	52.0	34.49
Design B3	30	2000	16	16	24	35.4	52.0	31.92
Design B4	40		16	16	25	36.1	52.0	30.64
Design B5	50		16	16	28	38.1	52.0	26.79
Design C1	10		16	16	16	30.1	52.0	42.19
Design C2	20		16	16	18	31.4	52.0	39.62
Design C3	30	1000	16	16	20	32.7	52.0	37.06
Design C4	40		16	16	22	34.1	52.0	34.49
Design C5	50		16	16	24	35.4	52.0	31.92

3.2 Effects of OSD Application on Steel Truss Bridge's Internal Forces

OSD panel redecking implies a deck and bridge's self-weight reduction. Based on the structural model developed using SAP2000, the internal forces on the steel truss bridge mainframe were reduced (see Figure 6). Moreover, Figures 7a and 7b show the axial tension and compression forces reduction on the steel truss bridge mainframe, with values of 20.6% - 24.6% and 20.5% - 24.5%, respectively.

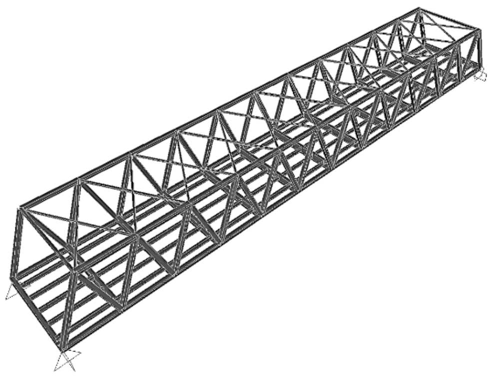


Figure 6. Structural model using SAP2000

3.3 OSD Application Effects on Inventory Rating Factor

The A-class steel truss bridge Bina Marga design standard with 60 m spans using RC decks has an inventory rating factor of 1.13192. Using the OSD panel increased the inventory rating factor value by 9.3%-9.5%, as shown in Figure 8. This is due to the self-weight and internal forces reduction on the steel truss bridge mainframe.

The inventory rating factor escalation is in accordance with Equation (1), where the nominal capacity of the structural element and the internal forces due to live loads are constant. However, the internal forces due to self-weight reduced, culminating in an escalation of the inventory rating factor (Directorate General of Highways, 2011).

In other words, using the OSD panel lighter than the existing RC decks increases the steel truss bridge capacity to resist the live load (vehicle rating) throughout its service life.

4 CONCLUSION

The OSD panels were evaluated concerning the strength, service, and fatigue limit states according to AASHTO LRFD Bridge Design Specifications 2012. Furthermore, the design process considered the variation of service life design, namely 10, 20, 30, 40, and 50 years, as well as the average daily traffic of 1000, 2000, and 3000 trucks/day. The design results showed that the thickness of the plates was 16-28 mm, ribs 16-19 mm, and floor beams 16-19 mm. OSD panel redecking implies a bridge's self-weight reduction. Based on the structural model developed using SAP2000, the bridge's self-weight reduced the axial tension and compression forces on the steel truss bridge mainframe by 20.6%-24.6% and 20.5%-24.5%, respectively. Consequently, this increased the inventory rating factor by 9.3%-9.5%. In other words, using the OSD panel lighter than the existing RC decks increases the steel truss bridge capacity to resist the live load or vehicle rating throughout its service life.

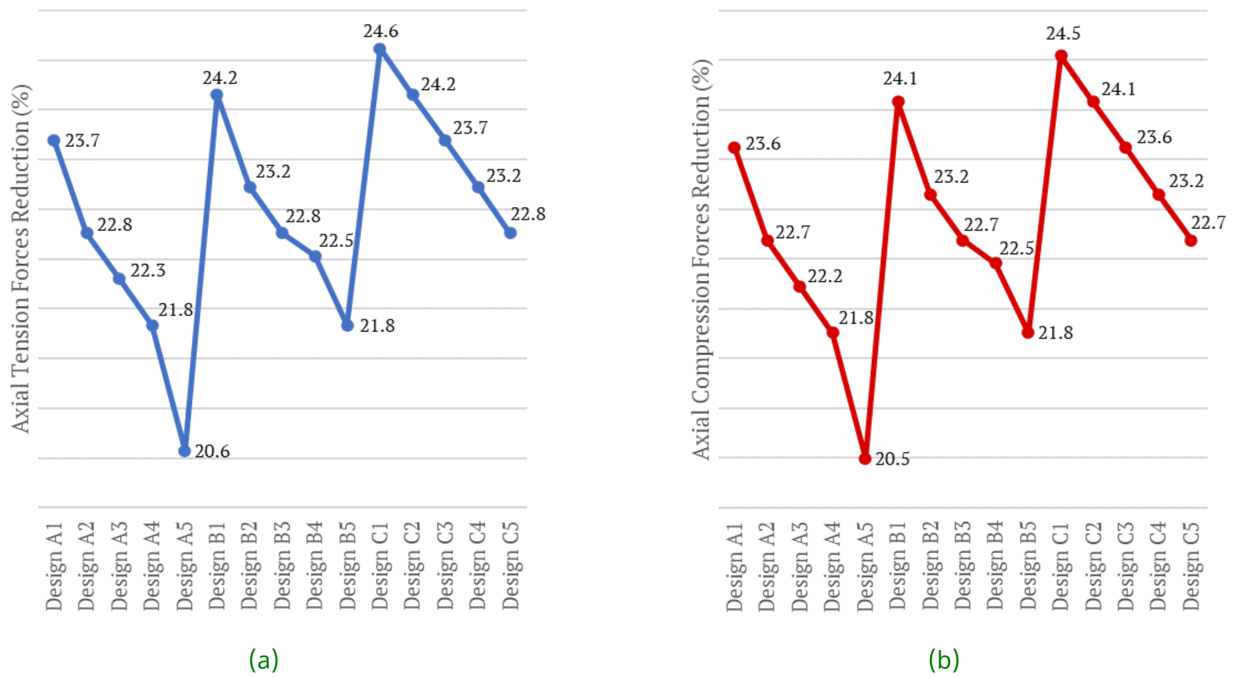


Figure 7. (a) Axial Tension and (b) Compression Forces Reduction on the Steel Truss Bridge Mainframe due to OSD Panel Redecking

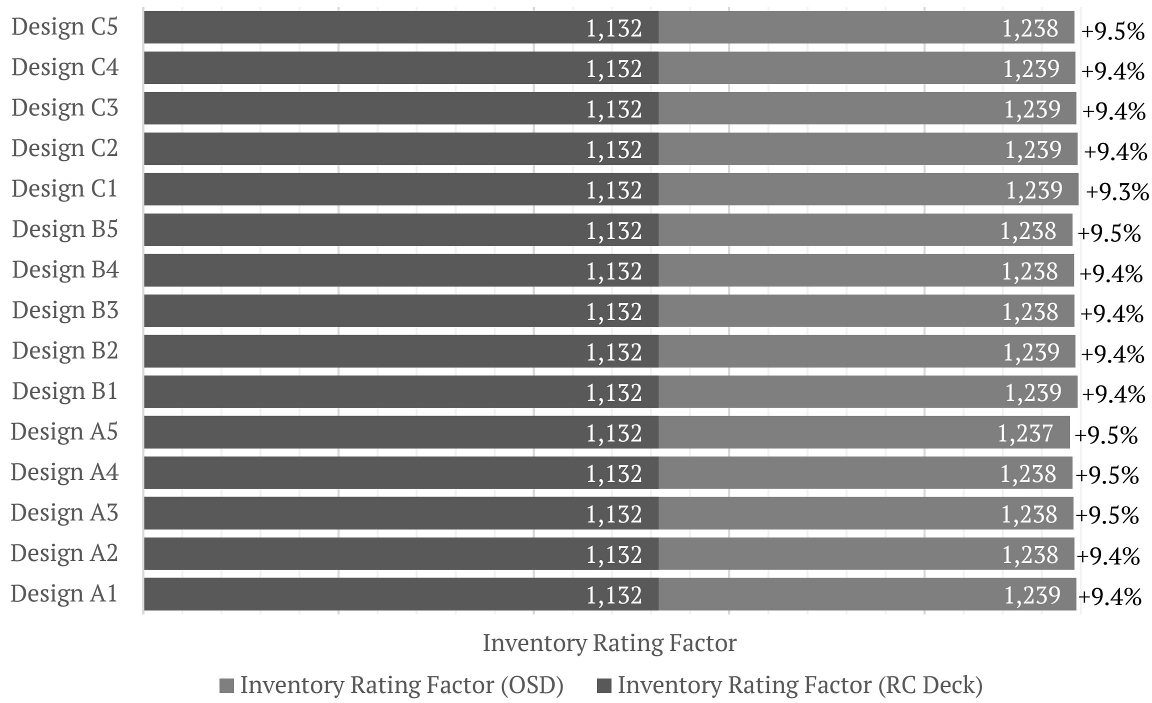


Figure 8. The Inventory Rating Factor Escalation due to OSD Panel Redecking

DISCLAIMER

The authors declare that there is no conflict of interest.

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