The 2023 World Congress on
Advances in Structural Engineering and Mechanics (ASEM23)
GECE, Seoul, Korea, August 16-18, 2023

Reliability Assessment of Cable Element in Jembatan Merah Putih Cable-Stayed Bridge Using Weigh-In-Motion Vehicle Data

*Widi Nugraha[1)], Indra Djati Sidi[2)], Made Suarjana[3)] and Ediansjah Zulkifli[4)]

[1)]Directorate General of Highway, Ministry of Public Works and Housing, Jl Nasution 264 Bandung, Indonesia
[1), 2), 3), 4)] Department of Civil Engineering, Institut Teknologi Bandung, Jl Ganesha 10 Bandung, Indonesia
[1)] widi.nugraha@pu.go.id

ABSTRACT

Jembatan Merah Putih is a cable-stayed bridge spanning across Teluk Dalam Pulau Ambon in Ambon City, Maluku Province, Indonesia. The bridge connects Desa Rumah Tiga in Sirimau District on the north side with Desa Hative Kecil/Galala in Teluk Ambon District on the south side, and has a length of 1,140 meters, making it one of the longest bridges in Eastern Indonesia. Reliability assessment of the cable element of the bridge was conducted using one-year Weigh-In-Motion (WIM) measurement vehicle data from the Central Java National Road Bridge-WIM (B-WIM) system, which has high traffic density and traffic load. A model of the bridge was created using Finite Element Method (FEM), and vehicle loading was simulated on the model to determine the load effect on the cable element. The load effect was found to follow a lognormal distribution, and the obtained value was projected using Extreme value theory to the 75-year return period, which is the bridge's design lifetime. To assess the reliability, First-Order Reliability Method (FORM) and Rosenblatt transformation were used, resulting in a reliability index of 3.85, which is higher than the reliability target set for important bridges in Indonesia (3.72). The findings suggest that the cable element of the Jembatan Merah Putih cable-stayed bridge is reliable and safe for use. The study provides valuable insights into the reliability assessment of cable-stayed bridges and highlights the importance of such assessments for ensuring the safety of bridges in Indonesia.

Keywords: Jembatan Merah Putih, cable-stayed bridge, reliability assessment, Weigh-In-Motion, Finite Element Method

1. INTRODUCTION

Jembatan Merah Putih, a stunning cable-stayed bridge, stands tall in the heart of Ambon City, Maluku Province, Indonesia. The bridge spans across Teluk Dalam Pulau

---

[1)] PhD. Student
[2)] Professor
[3)] PhD.
[4)] PhD.

Ambon, connecting Desa Rumah Tiga in Sirimau District on the north side with Desa Hative Kecil/Galala in Teluk Ambon District on the south side. Considered one of the longest bridges in Eastern Indonesia, Jembatan Merah Putih has become a new icon for Ambon City, attracting tourists from far and wide. The bridge, shown in Fig. 1, spanning 1,140 meters long, is divided into three parts, making it an impressive feat of engineering. The construction of this magnificent bridge has significantly reduced travel time between Pattimura Airport in Lei Hitu, Central Maluku, and Ambon City in Lei Timur to the south. Before its construction, travelers had to navigate a 35 km distance around Teluk Ambon, taking 60 minutes or a 45-minute ferry ride (Kementerian PUPR 2016).

Fig. 1 Jembatan Merah Putih Cable-stayed bridge (Kementerian PUPR 2016)

In addition to its aesthetic appeal, the Jembatan Merah Putih plays a crucial role in the economic development of Ambon City. Rapid infrastructure development is essential for driving economic growth in the region, and the local government has made the bridge a priority project. Its construction has already had a significant positive impact on the city and surrounding areas, according to Dermawan and Patty (2022). The bridge has not only reduced travel time between the airport and the city center, but it has also improved connectivity between various parts of the region. This improved connectivity has opened up new opportunities for trade and commerce, benefitting the local economy in many ways.

The reliability of the cable element of the Jembatan Merah Putih cable-stayed bridge is critical to its safety. To ensure the bridge's longevity and prevent potential failure, it is necessary to conduct reliability assessments of its cable element. The research conducted by Hou, Sun, and Chen (2020) emphasizes the importance of such assessments and use vehicle load data from Weigh-In-Motion (WIM) measurement and wind loading measurement to calculate the cable reliability index. Previous research by Ohorella and Harsoyo in 2017 has shown that the bridge has good stability against aerodynamic effects caused by wind. However, with the increasing traffic potential on the bridge, it is essential to evaluate the bridge's behavior under the vehicle load to ensure its safety and structural reliability. To assess Jembatan Merah Putih cable-stayed bridge reliability, a study was conducted using the one-year WIM measurement vehicle data collected from the Bridge WIM (B-WIM) system installed at the North Coast National Road of Central Java. This B-WIM system has higher traffic density and load compared to other B-WIM sites in Indonesia, making it a suitable source of data for reliability assessment (Nugraha et al. 2022).

WIM technology has become a widely used method for collecting traffic data on highways and bridges. It provides a non-intrusive way of measuring the weight and speed of vehicles as they pass over a sensor (Haugen et al. 2016). B-WIM is a type of WIM that uses sensors installed on a bridge to measure the weight and speed of vehicles passing over it (Nugraha and Sukmara 2018). The collected data can include vehicle type, speed, gross vehicle weight, axle configuration, and each respective axle load (Hang, Xie, and He 2013). This information can be used for various purposes, such as monitoring bridge health, assessing the impact of heavy vehicles on the bridge, and determining the tolls for vehicles passing over the bridge (Kalin, Znidarič, and Kreslin 2015). In this study, the B-WIM measurement data is used to assess the reliability of cable elements on a cable-stayed bridge by simulating vehicle loading and calculating the cable forces induced by the load.

To determine the load effect on the cable element of the Jembatan Merah Putih, a model of the bridge was created using the Finite Element Method (FEM). The vehicle loading from B-WIM measurements was simulated on the model to investigate the load effect on the cable element. Previous studies have shown that the load effect on bridge elements is a random variable with a unique distribution that can differ from the vehicle load distribution due to factors such as axle distance, axle load, and bridge length, which affects the number of vehicles that can fit on the bridge deck at full length simultaneously (Hou, Sun, and Chen 2021). This research will study the daily maximum load effect distribution on the cable element and project it to a 75-year return period, which will be calculated using Extreme Value Theory (Anitori, Casas, and Ghosn 2017).

In this study, the reliability of the cable element of the cable-stayed bridge will be assessed using the First-Order Reliability Method (FORM) and Rosenblatt transformation (Rosenblatt 1952). The resulting reliability index will be evaluated and compared with the target reliability of 3.72 set for Jembatan Merah Putih cable-stayed bridge, as it is classified as an important bridge in Indonesia. The cable reliability findings of Jembatan Merah Putih cable-stayed bridge will be discussed and summarized.

2. MERAH PUTIH BRIDGE FEM MODEL

The Jembatan Merah Putih cable stayed bridge's main span comprises of two pylons and their respective cable stayed system with a length of 300 meters. The pylon height is 89.50 meters from the pile cap, while the pile cap height is 6 meters. The deck has a width of 21.50 meters, consisting of a two-way road with two lanes for each way, where one lane width is 3600 millimeters, 500 millimeters median, and 1500 millimeters sideline. The height of the deck system, which consists of composite steel girder with concrete slab, is 2.55 meters. The materials used for the slab and pylon are compressive strength f_c' of 40 MPa concrete, while the pile cap uses compressive strength f_c' of 30 MPa concrete. The material used on the steel girder is ASTM A709M grade 345 with a yield strength f_y of 345 MPa and an ultimate strength fu of 450 MPa. The material used for the prestress tendon is ASTM A416 grade 270 low relaxation-strand with a yield strength f_{py} of 1670 MPa. The material used for the cable is steel strand with a breaking load f_{pu} of 1770 MPa and an allowable stress of 0.45 f_{pu}, which is 796 MPa.

The FEM model was created using Midas Civil software based on the detailed information of the bridge. The FEM model was created specifically to calculate the cable forces caused by the vehicle load, which was based on B-WIM measurement. To create the model, beam elements were used to model the bridge girders and the pylon, while tension-only elements were used to model the cables. The bearing restraints between the girders and pylons were modeled according to specifications. The bearing was simulated as a spring with three directions, and the spring stiffness of the constrained direction was set at 1×10^8 kN/m while the spring stiffness of the unconstrained direction was set to zero. The steel composite girders with reinforced concrete slabs as the deck system, and the pylons were modeled in detail. The FEM model created, which is depicted in Fig. 2, provides a comprehensive representation of the bridge and its components, allowing for accurate analysis of the cable forces induced by the vehicle load.

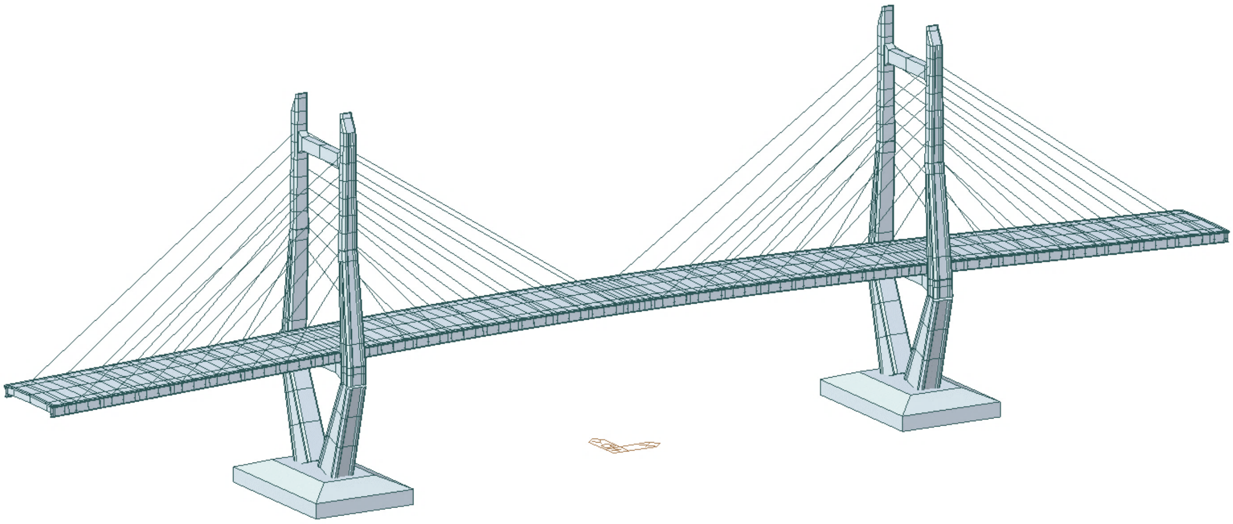

Fig. 2 FEM model for Merah Putih Cable-stayed bridge

In order to assess the stability of Jembatan Merah Putih, a moving load analysis was conducted using a simulation of a 300-meter-long queue of vehicles, equivalent to the length of the bridge. This was based on B-WIM daily measurement data, and the headway between vehicles was modeled based on the timestamp of the measurement. The number of load cases per day varied depending on the number of vehicles measured by the B-WIM. One of the heaviest load cases was taken from December 2nd, 2018, consisting of 32 vehicles with a total length of 298.2 meters. The vehicles in this load case were listed in Table 1, with the heaviest vehicle being vehicle no. 11, which was a 6-axle vehicle with a 95.2 ton GVW. There were four vehicles with a GVW greater than 50 tons in the list, which would significantly impact the cable force of the Jembatan Merah Putih stay cable.

Table 1 One of the heaviest load cases from December 2nd, 2018

No	Vehicle Subclass	Axle Load (ton)						Gross Vehicle Weight (ton)	Axle Distance (m)					Total Length (m)
		W1	W2	W3	W4	W5	W6		A1	A2	A3	A4	A5	
1	111	6.92	6.56	6.56	9.53			29.56	3.32	1.44	10.39			15.16
2	30	3.38	10.12					13.49	3.27					3.27
3	101	3.74	4.57	2.98	2.98			14.27	3.16	9.49	1.51			14.16
4	51	5.61	14.06	14.06				33.74	5.60	1.46				7.06
5	102	5.21	25.21	16.05	16.05	16.05		78.58	3.30	6.41	1.39	1.39		12.49
6	51	9.13	15.75	15.75				40.63	5.66	1.46				7.13
7	41	6.08	11.57					17.65	5.76					5.76
8	41	8.59	20.46					29.05	5.77					5.77
9	30	2.83	8.01					10.84	3.30					3.30
10	41	6.86	10.50					17.36	5.96					5.96
11	120	6.40	17.69	17.69	17.81	17.81	17.81	95.22	3.25	1.34	6.28	1.37	1.34	13.56
12	120	5.25	12.18	12.18	11.73	11.73	11.73	64.80	2.72	1.36	4.06	1.33	1.36	10.83
13	30	3.02	7.47					10.49	3.13					3.13
14	41	6.30	11.54					17.85	5.83					5.83
15	41	6.12	10.52					16.64	5.79					5.79
16	30	2.78	4.00					6.78	3.36					3.36
17	41	3.61	7.50					11.11	5.28					5.28
18	30	2.54	7.31					9.86	3.37					3.37
19	20	0.89	1.03					1.92	2.53					2.53
20	51	5.66	9.31	9.31				24.29	5.02	1.48				6.50
21	41	5.76	9.48					15.24	5.88					5.88
22	102	8.45	20.94	16.61	16.61	16.61		79.23	3.46	6.10	1.33	1.33		12.22
23	40	2.46	12.69					15.15	3.98					3.98
24	51	7.81	13.12	13.12				34.05	5.75	1.53				7.27
25	41	6.21	9.41					15.62	5.85					5.85
26	51	7.82	12.76	12.76				33.33	5.65	1.47				7.12
27	51	6.38	9.56	9.56				25.50	4.94	1.47				6.41
28	30	2.82	9.19					12.01	3.06					3.06
29	51	4.34	2.72	2.72				9.77	5.78	1.42				7.19
30	30	3.81	10.38					14.19	3.33					3.33
31	51	5.16	4.08	4.08				13.33	5.69	1.37				7.05
32	30	3.05	9.99					13.04	3.31					3.31

To accurately evaluate the impact of vehicle loading on the Jembatan Merah Putih, a moving load analysis was conducted using a realistic scenario. This involved inputting the axle load and distance of all 32 vehicles from one of the heaviest load cases on Table 1 above into Midas Civil as a single train moving load. By using a B-WIM measurement data, a more accurate simulation of the actual load effect on the bridge was achieved. This simulation was repeated for another load case and then for each day in a year's worth of data. The daily maximum cable force due to the moving load vehicle analysis result was then projected to the 75-year return period of maximum cable force for the next step of analysis. By conducting this analysis, a more realistic picture of the impact of vehicle loading on the Jembatan Merah Putih could be obtained, allowing for better assessment of its reliability.

3. STATISTICAL ANALYSIS

The reliability assessment in this research will use a performance function $R - D - L > 0$, where R represents the resistance or capacity, D represents the dead load effect, and L represents the live load effect. To use the FORM method, the resistance and load distribution must be normal or transformed using Rosenblatt transformation. This study will represent values as cable force for both resistance and load. As for live load effect on cable force, the daily maximum cable force from FEM model moving load analysis due to B-WIM vehicle loading was projected using Extreme value theory to obtain the 75-year return period of maximum cable force. The research found that the distribution of the 75-year return period of maximum cable force was in line with the Gumbel Extreme type I, as governed by Equation (2) and (3). Equation (2) is the distribution of daily maximum load effects and Equation (3) is a projection factor based on the Gumbel Type I distribution. This allows the estimated mean maximum load effects for a 75-year return period to be determined based on the distribution of daily maximum load effects based on one-year worth B-WIM measurement data.

$$F_{X(1\,day)}(x) = e^{\left(-e^{-\frac{x-u}{\alpha}}\right)} \tag{2}$$

where u is location parameter and α is scale parameter.

$$F_{X(75\,year)}(x) = \left\{F_{X(1\,day)}(x)\right\}^N = e^{\left(-e^{-\frac{x-u_n}{\alpha_n}}\right)} \tag{3}$$

where N is number of days in 75 years, $u_n = u + \alpha \ln N$ is location parameter of the 75-year return period distribution, and α_n is scale parameter of the 75-year return period distribution, where $\alpha_n = \alpha$.

Fig. 3 depicts the Cumulative Distribution Function (CDF) projection of the 75-year return period maximum cable force due to live load from the daily maximum cable force due to live load using Extreme value theory of Jembatan Merah Putih Cable Stayed Bridge. The scattered gray dots in the figure represent the data of cable force sorted from lowest to highest, showing a clear distribution pattern. This data was fitted with Gumbel type 1 for 1-day, represented as the dark blue curve in the figure. The figure shows that the Gumbel distribution accurately describes the daily maximum tension cable forces. By using Equation (3), the CDF for the 75-year maximum tension cable force for Jembatan Merah Putih Cable Stayed Bridge is shown in the figure as the light blue curve on the right. It is clear that the distribution moves to the right as the value of the cable force rises due to the projection from 1-day return period to 75-year return period. The mean and standard deviation from the distribution of 75-year return period maximum tension cable force can be used for the next step, the reliability analysis.

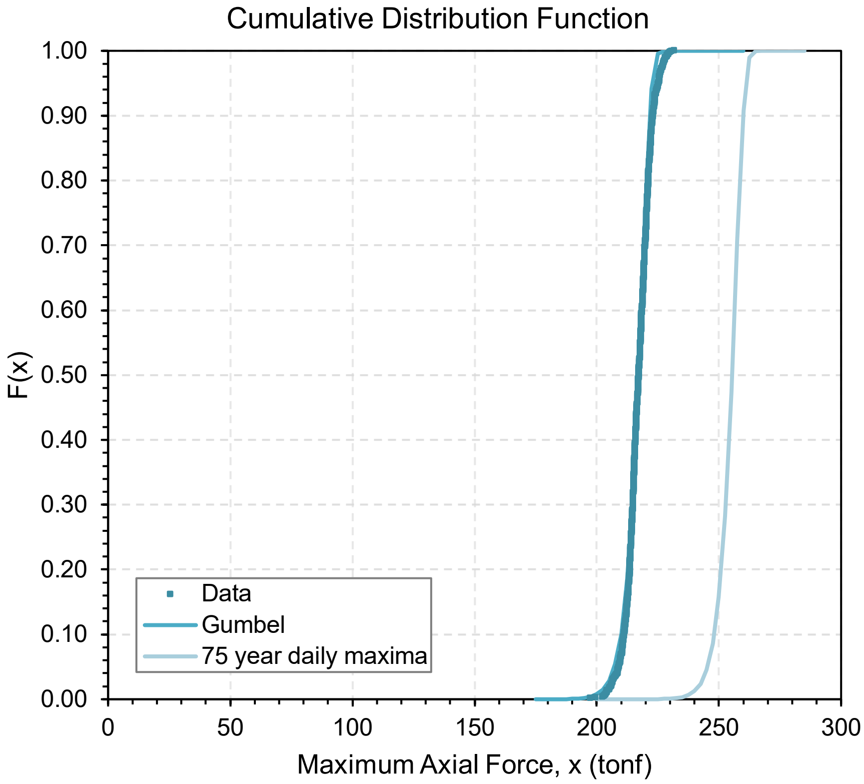

Fig. 3 Distribution of 75 year daily maximum cable force

$$\mu_L = u_n + \gamma \times \sigma_n \tag{4}$$

$$\sigma_L = \sqrt{\frac{\pi^2 \times \sigma_n}{6}} \tag{5}$$

where $\gamma = 0.577$ is the Euler number

After determining the distribution of the 75-year return period maximum cable force due to live-load from Fig. 3, the next step was to calculate the mean and standard deviation of the maximum live-load effect for a 75-year return period. Equation (4) and (5) were used to obtain the mean and standard deviation, respectively. The mean value was calculated as 258.89 tonf, while the standard deviation was found to be 2.51 tonf. These values can be used in the reliability analysis of Jembatan Merah Putih to assess its ability to withstand maximum cable force due to live load.

In order to determine the cable force of Jembatan Merah Putih due to dead load effect, a structural analysis was performed based on the assumption that the distribution follows a normal distribution (Iatsko and Nowak 2021). The dead load effect values were obtained by inputting the nominal densities of various structural materials used in the bridge, as well as the superimposed dead load such as the weight of the asphalt layer, pedestrian deck, and the parapet on both sides of the bridge. The nominal values resulting from the dead load and SIDL were calculated through structural analysis and then converted into average values for the calculation of the reliability index. The 1999 LRFD research on the statistical properties of loading components showed that the ratio of the average value to the nominal value of the dead load effect is $\frac{\mu_D}{\mu_{D_n}} = 1.05$ (Nowak et al. 1999). With an appropriate coefficient of variation (c.o.v.) of $\Omega_D = 0.10$, the average value and standard deviation of the cable force due to the dead load effect were calculated as $\mu_D = 1.05\mu_{D_n}$ and $\sigma_D = \Omega_D\mu_D$, respectively.

After the mean and standard deviation values for the load effect variables (dead load and live load) were determined, the next step was to determine the mean and standard deviation for resistance. To estimate these values, the bias factor and coefficient of variation (COV) recommended by Hou in 2020 for the cable-stayed bridge being analyzed were used. The resistance of the stay cable was calculated based on the nominal material properties and the design area specified in the drawing. The bias factor was applied to the nominal resistance value to obtain the average value of the resistance, while the standard deviation was calculated using the COV value and the average resistance value. This allowed for the determination of the reliability index of Jembatan Merah Putih by using the calculated mean and standard deviation values for both the load effect variables and resistance.

4. RELIABILITY OF THE CABLES

Reliability is the fundamental principle in structural design that enables quantifying the probability of a structure's intended function for a given time under certain conditions while considering the uncertainties associated with loads, material properties, and other factors. The Load and Resistance Factor Design (LRFD) method utilizes this principle to ensure the safety of structures. Performance function is used to calculate the reliability index of the structure, which represents the difference between resistance and loads considered. The performance function used in this research is $R - D - L > 0$, so the reliability index can be calculated using FORM as defined by Equation (6) which is proposed by Ang and Tang in 1975. The assumption used in this Equation are the resistance and the loads are normally distributed and independent of each other. The non-normal distributed variable must be transformed using Rosenblatt transformation (Rosenblatt 1952).

$$\beta = \frac{\mu_R - \mu_D - \mu_L}{\sqrt{(\sigma_R)^2 + (\sigma_D)^2 + (\sigma_L)^2}} \tag{6}$$

where μ_R= the mean value of resistance or cable capacity; μ_D= the mean value of cable force induced by the dead load; μ_L= the mean value of cable force induced by the live load; σ_R = the standard deviation of resistance or cable capacity; σ_D = the standard deviation of cable force induced by the dead load; and σ_L = the standard deviation of cable force induced by the live load.

Table 2 Iteration on reliability index calculation

Iteration No.	Failure points		F_L	f_L	σ_L^N	σ_R^N	μ_L^N	μ_R^N	Reliability index (β)
	l*	r*							
1	258.90	1393.89	0.570	0.0084	47.03	165.51	250.57	1384.07	3.821
2	298.07	795.77	0.857	0.0036	74.04	94.49	295.82	1236.23	3.794
3	457.90	972.24	0.967	0.0006	113.74	115.44	222.47	1315.64	3.801
4	514.65	1014.64	0.979	0.0002	127.84	120.48	179.08	1329.70	3.842
5	525.20	1022.29	0.983	0.0002	130.46	121.39	170.18	1332.05	3.852
6	526.74	1023.36	0.983	0.0002	130.84	121.51	168.86	1332.37	3.854
7	526.96	1023.51	0.983	0.0002	130.89	121.53	168.67	1332.42	3.854
8	526.99	1023.53	0.983	0.0002	130.90	121.53	168.65	1332.43	3.854
9	526.99	1023.54	0.983	0.0002	130.90	121.53	168.64	1332.43	3.854
10	526.99	1023.54	0.983	0.0002	130.90	121.53	168.64	1332.43	3.854

After all variables were defined and calculated, the reliability index was computed for the stay cable of Jembatan Merah Putih. To account for non-normally distributed variables, the Rosenblatt transformation was applied to transform the variables into the normal distribution. The iterative process is shown in Table 2, which resulted in a reliability index of 3.85. This value indicates that the cable-stayed bridge is reliable and safe for the expected traffic loads, as it is higher than the target reliability of important bridges in Indonesia, which is 3.72. This means that the design of the stay cable of Jembatan Merah Putih cable-stayed bridge is robust and can withstand extreme traffic loading conditions. The traffic loading data used for the evaluation was from the B-WIM measurement in North Coast National Road in Central Java, which has relatively high volume and heavy traffic loading compared to other B-WIM measurement sites. Therefore, the Jembatan Merah Putih cable-stayed bridge has a margin of safety against the target reliability.

The reliability of a structure is a crucial aspect in ensuring that it performs its intended function under given conditions for a specific period of time. The reliability is directly linked to the probability of failure, and it is necessary to consider various uncertainties that are associated with loads, material properties, and other factors in order to accurately determine the reliability index of a structure. A target reliability level must be specified, which indicates the acceptable failure probability when the resistance, considered as a random variable, is smaller than the loads effect on the structural elements (Lee et al. 2016). The higher the reliability index of a structure is, the more dependable and reliable it is, and the smaller the risk of failure. However, it also means that the cost of building the structure is higher. It is possible to optimize the design of the structure to meet the target reliability, but it should not be significantly higher than the target specified by the code to avoid overdesign and excessive costs (Ghasemi and Nowak 2017).

In the case of the Jembatan Merah Putih cable-stayed bridge, the reliability index results indicate that the bridge is sufficiently reliable and safe for the expected traffic loads, as the reliability index is higher than the target reliability of important bridges in Indonesia. Therefore, there is no need to optimize the cable design further.

However, it is important to note that wind and temperature-induced cable force have not been considered in this study. Future research should focus on evaluating the effects of these factors on the reliability of the bridge. The wind can generate significant loads on the bridge, and temperature changes can affect the properties of the materials, which in turn can affect the bridge's reliability (Dieng et al. 2016). Therefore, it is important to consider these factors to ensure that the bridge is safe and reliable under all conditions.

5. CONCLUSIONS

In conclusion, this research presents a methodology to assess the reliability of the Jembatan Merah Putih cable-stayed bridge under vehicle loading. The simulation of vehicle loading on the bridge model was done using moving load analysis, and the daily maximum cable force due to moving load vehicle analysis result was used to obtain the distribution using Extreme Value Theory. The research has considered various factors, including dead load and live load effect, cable resistance, and statistical properties of loading components. The reliability assessment was conducted using a performance function and the FORM method. The resulting reliability index was 3.85, which is higher than the target reliability of 3.72 for important bridges in Indonesia.

Therefore, the Jembatan Merah Putih cable-stayed bridge has a sufficient level of reliability under vehicle loading and is able to perform its function as a critical infrastructure for transportation, especially in Eastern Indonesia. The findings of this research can be used as a reference for the design and assessment of other cable-stayed bridges with similar characteristics, as well as for the maintenance and management of Jembatan Merah Putih to ensure its continued safe operation.

For future research, it is recommended to investigate the wind and temperature-induced cable forces on the bridge. These factors can significantly affect the cable forces and, therefore, the reliability of the bridge. Wind and temperature-induced cable forces are essential for the evaluation of the reliability of cable-stayed bridges, especially in areas with high wind loads and temperature changes. Therefore, it is crucial to consider these factors in the design and evaluation of cable-stayed bridges.

ACKNOWLEDGMENTS

We would like to express our gratitude to the Indonesia Endowment Fund for Education (LPDP) and the Ministry of Public Works and Housing Republic (MPWH) of Indonesia for their support and funding for this research project. Without their generous support, this research would not have been possible. We are also thankful to all the individuals and institutions who have provided their assistance and cooperation during this study. Do note that all findings and conclusions are those of the writers and do not represent LPDP or MPWH.

REFERENCES

Ang, A H S, and W H Tang. 1975. *Probability Concepts in Engineering Planning and Design, Basic Principles*. Probability Concepts in Engineering Planning and Design. Wiley. https://books.google.co.id/books?id=EIRRAAAAMAAJ.

Anitori, Giorgio, Joan R. Casas, and Michel Ghosn. 2017. 'WIM-Based Live-Load Model for Advanced Analysis of Simply Supported Short- and Medium-Span Highway Bridges'. *Journal of Bridge Engineering* 22 (10). https://doi.org/10.1061/(ASCE)BE.1943-5592.0001081.

Dermawan, Hans, and Christy Vianty Patty. 2022. ‘Analisis Life Cycle Cost Pada Proyek Jembatan Merah Putih Di Kota Ambon Dengan Pendekatan Nilai Ekuivalensi’. *Teras Jurnal* 12 (2): 561–71. https://doi.org/10.29103/tj.v12i2.769.

Dieng, L., C. Girardeau, L. Gaillet, Y. Falaise, A. Žnidarič, and M. Ralbovsky. 2016. ‘Bridge Assessment Using Weigh-in-Motion and Acoustic Emission Methods’. In *Conference Proceedings of the Society for Experimental Mechanics Series*, 2:205–15. https://doi.org/10.1007/978-3-319-29751-4_21.

Ghasemi, Seyed Hooman, and Andrzej S. Nowak. 2017. ‘Target Reliability for Bridges with Consideration of Ultimate Limit State’. *Engineering Structures* 152: 226–37. https://doi.org/10.1016/j.engstruct.2017.09.012.

Hang, Wen, Yuanchang Xie, and Jie He. 2013. ‘Practices of Using Weigh-in-Motion Technology for Truck Weight Regulation in China’. *Transport Policy* 30. https://doi.org/10.1016/j.tranpol.2013.09.013.

Haugen, Torbjørn, Jorunn R. Levy, Erlend Aakre, and Maria Elena Palma Tello. 2016. ‘Weigh-in-Motion Equipment - Experiences and Challenges’. In *Transportation Research Procedia*. Vol. 14. https://doi.org/10.1016/j.trpro.2016.05.215.

Hou, Ning, Limin Sun, and Lin Chen. 2020. ‘Cable Reliability Assessments for Cable-Stayed Bridges Using Identified Tension Forces and Monitored Loads’. *Journal of Bridge Engineering* 25 (7): 1–12. https://doi.org/10.1061/(asce)be.1943-5592.0001573.

———. 2021. ‘Modeling Vehicle Load for a Long-Span Bridge Based on Weigh in Motion Data’. *Measurement: Journal of the International Measurement Confederation* 183 (June): 109727. https://doi.org/10.1016/j.measurement.2021.109727.

Iatsko, Olga, and Andrzej S. Nowak. 2021. ‘Revisited Live Load for Simple-Span Bridges’. *Journal of Bridge Engineering* 26 (1): 1–14. https://doi.org/10.1061/(asce)be.1943-5592.0001647.

Kalin, Jan, Aleš Znidarič, and Maja Kreslin. 2015. ‘Using Weigh-in-Motion Data to Determine Bridge Dynamic Amplification Factor’. *MATEC Web of Conferences* 24. https://doi.org/10.1051/matecconf/20152402003.

Kementerian PUPR. 2016. ‘Jembatan Merah Putih’. 2016. https://twitter.com/kemenpu/status/721992692104728576?lang=en.

Lee, Seung Han, Ho Hyun Lee, Inyeol Paik, and Hae Sung Lee. 2016. ‘Evaluation of Load and Resistance Factors for the Reliability-Based Design of the Main Cables of Earth-Anchored Suspension Bridges’. *KSCE Journal of Civil Engineering* 20 (6): 2457–68. https://doi.org/10.1007/s12205-015-1442-5.

Nowak, A S, National Research Council (U.S.). Transportation Research Board, American Association of State Highway, Transportation Officials, and United States. Federal Highway Administration. 1999. *Calibration of LRFD Bridge Design Code*. NCHRP Report. Transportation Research Board, National Research Council. https://books.google.co.id/books?id=XwIFAQAAIAAJ.

Nugraha, Widi, Indra Djati Sidi, Made Suarjana, and Ediansjah Zulkifli. 2022. ‘Reliability Evaluation of Steel Truss Bridge Due to Traffic Load Based on Bridge Weigh-in-Motion Measurement’. *Structural Monitoring and Maintenance* 9 (4): 323–36. http://www.techno-press.com/?page=container&journal=smm&volume=9&num=4.

Nugraha, Widi, and Gatot Sukmara. 2018. ‘Uji Coba Model Fisik Sistem Bridge Weigh in Motion Sederhana Pada Jembatan Gelagar Baja Komposit (Trial Model Of A Simple

Bridge Weigh in Motion …’. *Jurnal Jalan-Jembatan* 35 (1): 1–15.

Ohorella, Sumaiyah, and Harsoyo. 2017. ‘Analisis Kestabilan Cable Stayed Bridge Akibat Pengaruh Rasio Lebar Terhadap Bentang Jembatan’. *Teknisia* 22 (2): 359–71.

Rosenblatt, Murray. 1952. ‘Remarks on a Multivariate Transformation’. *The Annals of Mathematical Statistics* 23 (3): 470–72. http://www.jstor.org/stable/2236692.