

Reliability Analysis of Youtefa Steel Arch Bridge using WIM Vehicle Load Data

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Abstract

The Youtefa Bridge, completed in 2019, is a steel arch bridge that was constructed over Youtefa Bay in Papua, Indonesia. Its purpose was to connect the Holtekamp area in Muara Tami District with Hamadi in Jayapura Selatan District, providing better access to the surrounding facilities and supporting the economic development of Eastern Indonesia. In order to guarantee the bridge's reliability, a reliability analysis was conducted using Weigh-In-Motion (WIM) data. Over a year's worth of WIM vehicle load data was gathered, then projected using extreme value theory to determine the load effect of a 75-year return period for the bridge's service life. The results of the analysis indicate that the Youtefa Bridge boasts a reliability index of 5.39, exceeding the target reliability of bridges in Indonesia which stands at 3.72. This high reliability index suggests that the Youtefa Bridge can endure the anticipated loads with a remarkable level of reliability, ensuring the safety of its users. The findings of the reliability analysis underscore the significance of periodic evaluations of bridge reliability to ensure their continued safe operation, and the approach taken in this study could be applied to other bridge structures as well.

Keywords: Youtefa Bridge, Reliability analysis, Weigh-In-Motion (WIM), Extreme value theory, Target reliability

Introduction

The Youtefa Bridge is a remarkable feat of engineering that has greatly improved transportation and economic development in Eastern Indonesia. Completed in 2019, this steel arch bridge spans Youtefa Bay in Papua, Indonesia, connecting the Holtekamp area in Muara Tami District with Hamadi in Jayapura Selatan District. The bridge was designed to provide better access to surrounding facilities and support the growth of the region. In fact, research has shown that the existence of the Youtefa Bridge has caused an enhancement of the community's economy, especially in Holtekamp Beach by providing a direct link between Holtekamp and Hamadi, it has reduced travel times and facilitated trade between these two areas (Sari, Brabar, and Agustinus 2021). Constructed using high-strength steel and reinforced concrete, the Youtefa Bridge boasts a number of unique features that make it stand out from other bridges. For example, its arch design allows for a longer span over Youtefa Bay with minimum need for intermediate supports. This not only enhances its aesthetic appeal but also minimizes its impact on the environment. Arch steel bridges have several benefits. One of their main advantages is their high level of resistance to bending forces due to their curved design. This allows them to span greater distances than other bridge designs (Nugraha et al. 2017). Not only has the bridge had a significant impact on local development, but it has also broken two records according to MURI (Museum Rekor Indonesia). The first record is for delivering an intact steel arch bridge over the farthest distance. The second record is for installing the longest intact steel frame bridge (West Papua Diary 2021).

Youtefa Bridge, located in Papua, Indonesia, has several advantages over onsite steel arch girder installation either using bolt connection or in situ welding. As a prefabricated bridge, it is built in a separate location in Surabaya as a complete for each arch span, then transported to the construction site by boat for installation. Prefabricated bridges are a popular form of accelerated bridge construction with their own benefits and considerations (Nugraha and Chairulloh 2018). The main benefits of using prefabrication as compared to conventional construction are time savings of work done in site and also cost savings. The total cost of using prefabricated bridge elements (PBE) depends greatly on the scale of the prefabrication (Hällmark, White, and Collin 2012). The more that prefabrication is used, the lower the costs. Even under limited use, however, prefabrication is usually comparable to traditional construction techniques (Khan 2015). Additionally, the quality of the connection is more reliable and

controlled than on-site connection between steel members, whether bolt connection or welding connection (Culmo 2011).

The Youtefa Bridge as shown in Figure 1, is a remarkable structure that spans 400 meters, consists of two steel arches with a span of 150 meters each, plus two 50-meter tail arch spans on each side. With a width of 21 meters and clearance of more than 20 meters, the bridge provides ample space for two lanes of traffic in both directions. The bridge's height also exceeds 20 meters. To ensure its stability in an area prone to earthquakes, the Youtefa Bridge was designed with several advanced safety features. Its supports are equipped with seismic pendulum bearings that provide isolation from ground movements during an earthquake. Additionally, the bridge uses modular seismic expansion joints to enable deformation due to service and earthquake loads. The foundation of the Youtefa Bridge is constructed using reinforced concrete bored piles with a compressive strength of 35 MPa. These piles extend to depths ranging from 20 to 46 meters below ground level, providing a solid base for this impressive structure.



Figure 1 Youtefa Bridge, Papua (PUPR 2019)

In order to ensure the safety and reliability of this important infrastructure project, in this paper, a thorough reliability analysis was conducted using WIM Vehicle Load Data. WIM stands for Weigh-In-Motion and refers to systems that use sensors installed on the road or bridge to capture and record the axle weights and gross vehicle weights as vehicles drive over a measurement site (Sujon and Dai 2021). Unlike static scales, WIM systems are capable of measuring vehicles traveling at reduced or normal traffic speeds without requiring them to stop (Nugraha and Sukmara 2016). There are two main types of WIM systems: Bridge WIM (B-WIM) and pavement-based WIM. B-WIM is a particular WIM technology that uses an existing bridge as a weigh scale instead of using a pressure-sensitive sensor in the road pavement (ISWIM 2022). This has some advantages for bridge applications, such as durability, portability, and easy installation (Paul and Roy 2023). In addition to estimating the weight of passing vehicles, B-WIM also provides other structural information that is helpful for bridge assessment (Paul and Roy 2023).

Pavement-based WIM systems use sensors installed on the road to capture and record axle weights and gross vehicle weights as vehicles drive over a measurement site. These systems give vehicle weight estimates after direct contact with vehicle tyres (O'Brien et al. 2017). Both types of WIM systems exist, and each has its own advantages depending on the intended application. In this research, vehicle data from the B-WIM system installed by the Ministry of Public Works and Housing, Republic of Indonesia on the North Coast Central Java national road will be used to evaluate the Youtefa Bridge's reliability (Nugraha et al. 2022). An example of B-WIM measurement result is shown in Figure 3, which depicts a 6-axle vehicle with a weight of 75.20 tonf. The Youtefa Bridge is a crucial infrastructure in Papua that connects Jayapura city and its surrounding areas, and it is important to evaluate it by simulate medium to heavy traffic load data which is available from B-WIM measurement in Central Java. By

analyzing WIM Vehicle Load Data using simulated vehicles crossing the Youtefa Bridge model, we can gain insights into how well it is performing under real-world conditions.



Figure 2 B-WIM measurement result example, a 6-axle vehicle with a weight of 75.20 tonf

Reliability analysis of a structure involves assessing the safety and performance of the structure under various conditions. This can include evaluating the effects of traffic and wind loads on bridges, as well as other factors such as material properties and environmental conditions (Lu et al. 2022). The goal of reliability analysis is to determine the likelihood of failure or unacceptable performance and to identify ways to improve the safety and reliability of the structure (Nugraha and Sidi 2016). This analysis used reliability techniques for assessing the structural adequacy of bridges (Lark and Flaig 2005). Over a year's worth of WIM vehicle load data was gathered and projected using extreme value theory to determine the load effect of a 75-year return period for the bridge's service life (Nugraha et al. 2022). The resulting reliability index was then compared to a target reliability of 3.72, which represents a standard level of safety for bridges with a lifespan of 75 years (Ghasemi and Nowak 2017).

This paper presents the results of this analysis and discusses its implications for the continued safe operation of the Youtefa Bridge. The findings underscore the significance of periodic evaluations of bridge reliability and suggest that the approach taken in this study could be applied to other bridge structures as well.

Youtefa Bridge Structure Model

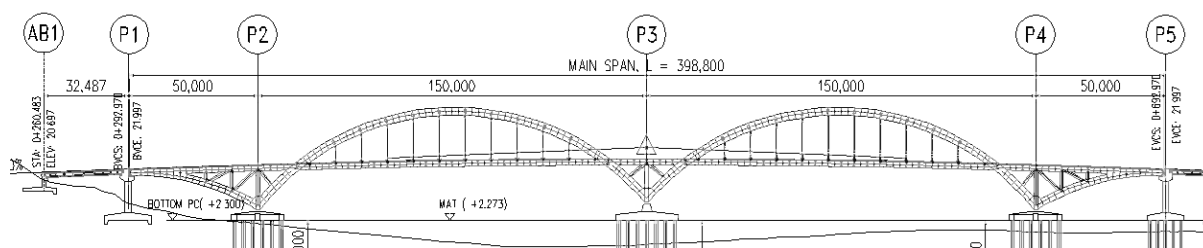


Figure 3 Youtefa Bridge Shop Drawing

To aid in the evaluation of the Youtefa Bridge's structural reliability, a Finite Element Model (FEM) was created based on the bridge's design drawings, structural member dimensions, and material specifications (as shown in Figure 3). This FEM model was constructed using Midas Civil software, which is commonly used for designing and analyzing bridge structures. The resulting FEM model of the Youtefa Bridge can be seen in Figure 4. The FEM model used in this research has been calibrated to match the structural behavior observed during a static loading test conducted in 2019 before the bridge

was open for traffic. Vehicle load data from WIM measurements was input into the FEM model to simulate moving loads. The WIM measurements provided detailed data on the vehicles including gross vehicle weight, vehicle axle weight, axle distances, and axle configurations. Using the WIM data collected over a one-year period, the daily maximum load effect on each structural member was calculated for each date of WIM data.

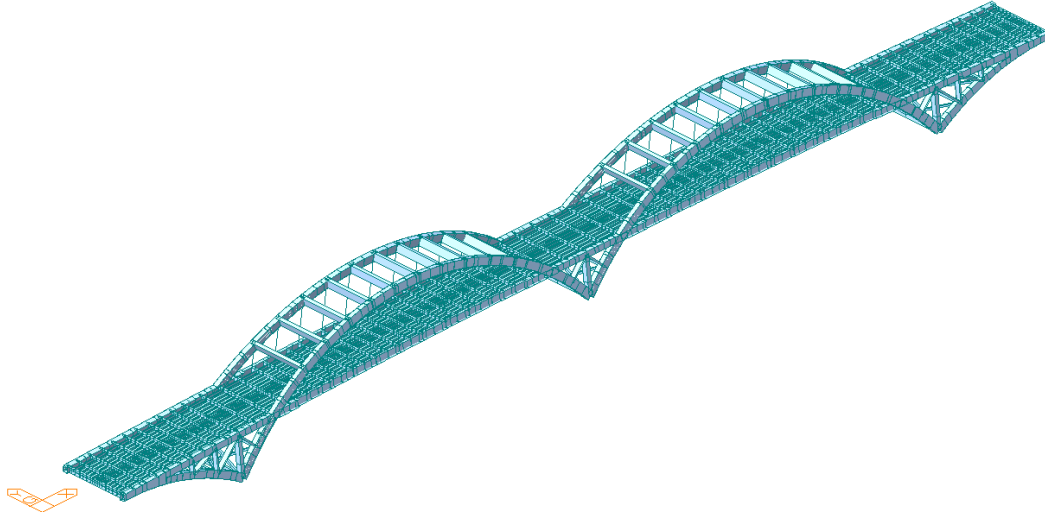


Figure 4 Youtefa Bridge FEM Model

WIM Vehicle load simulation

The vehicle load data used in this study was obtained from a Weigh-in-Motion (WIM) measurement conducted on the North Coast national road in Central Java within one year in 2018. The WIM measurement collected detailed vehicle data such as the timestamp when the vehicle passes, vehicle speed, the gross vehicle weight, vehicle axle weight, vehicle axle distances, and vehicle axle configurations. These data were used to construct a vehicle load sequence train for simulating fully traffic loading on a 400-meter length bridge model. From one day's measurement data, several vehicle load sequence trains were obtained and used as input for simulating moving loads in the bridge model. One of the vehicle load sequences with the largest vehicle load effect for a fully loaded 400-meter bridge length was recorded on 1 December 2018, as displayed in Table 1.

Table 1 Vehicle sequences for 400-meter bridge loading simulation from 1 December 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	30	4.66	18.87					23.52	3.39					3.39
2	51	10.82	11.62	11.62				34.06	6.03	1.54				7.57
3	30	3.51	7.80					11.31	3.34					3.34
4	51	7.38	22.22	22.22				51.83	3.89	1.49				5.38
5	30	3.97	13.91					17.88	3.18					3.18
6	30	5.42	17.64					23.06	3.18					3.18
7	51	9.53	23.23	23.23				55.98	5.70	1.50				7.19
8	51	9.04	21.27	21.27				51.58	5.74	1.52				7.26
9	30	4.24	13.14					17.38	3.27					3.27
10	51	10.61	21.00	21.00				52.61	5.66	1.53				7.19
11	51	14.82	20.29	20.29				55.41	5.90	1.52				7.43
12	30	2.60	9.01					11.60	3.26					3.26
13	51	12.17	18.63	18.63				49.44	4.06	1.50				5.56
14	41	7.01	12.54					19.54	5.80					5.80
15	61	3.92	5.99	3.64	5.47			19.02	4.78	5.61	4.62			15.01
16	63	7.29	11.03	11.03	14.40	14.40		58.16	3.19	6.74	1.46	1.46		12.85
17	40	4.55	6.08					10.63	3.78					3.78
18	58	4.77	4.77	3.16	3.16			15.87	1.84	4.68	1.29			7.80

19	41	6.24	11.41					17.66	5.78				5.78
20	41	7.21	12.61					19.82	5.72				5.72
21	30	4.26	10.42					14.68	3.35				3.35
22	51	5.02	19.52	19.52				44.06	4.06	1.41			5.47
23	41	5.33	7.08					12.42	5.34				5.34
24	41	7.22	12.17					19.40	6.03				6.03
25	41	7.27	11.45					18.72	6.00				6.00
26	41	7.07	11.96					19.03	5.99				5.99
27	51	4.69	5.01	5.01				14.72	3.11	1.44			4.55
28	41	6.55	9.98					16.53	5.10				5.10
29	41	6.43	8.57					15.00	4.77				4.77
30	40	2.26	3.94					6.19	3.96				3.96
31	102	5.91	23.62	19.35	19.35	19.35		87.58	3.11	7.85	1.26	1.26	13.48
32	102	5.49	9.89	7.71	7.71	7.71		38.51	3.30	6.61	1.34	1.34	12.58
33	102	6.67	26.71	17.16	17.16	17.16		84.84	3.06	7.79	1.25	1.25	13.35
34	51	7.74	7.31	7.31				22.37	5.94	1.57			7.50
35	30	3.79	13.71					17.50	3.21				3.21
36	30	3.21	6.88					10.09	3.29				3.29
37	51	4.55	6.89	6.89				18.34	5.60	1.38			6.98
38	41	9.36	11.17					20.53	6.48				6.48
39	40	2.62	2.14					4.76	3.74				3.74
40	30	3.60	2.22					5.82	3.35				3.35
41	120	7.66	19.20	19.20	18.21	18.21	18.21	100.70	3.62	1.37	6.49	1.40	14.26
42	30	3.16	5.36					8.52	3.31				3.31
43	40	2.31	4.80					7.12	4.03				4.03

Table 1 provides detailed data of 43 vehicles used in this research. Each vehicle has its own specific data, such as axle load and axle distance. To simulate medium to heavy traffic on the bridge, the distance between vehicles was assumed to be fixed at 5 meters. To improve the quality of the moving load analysis, the axle load and axle distance of all 43 vehicles were inputted as a single train moving load in Midas Civil. This allowed for a more accurate simulation of the actual load effect on the bridge. By using a fixed distance between vehicles, it was possible to create a realistic scenario of traffic on the bridge and evaluate its impact on the reliability of the Youtefa Bridge. Overall, the use of detailed vehicle data and a realistic simulation of traffic conditions enabled a more precise analysis of the reliability of the Youtefa Bridge, providing valuable information for future bridge design and construction.

The moving load analysis was conducted for one-year worth of measurement data, and the output is the load effects or internal forces for each structural member in the form of axial forces and bending moments for arch members, axial forces for hanger, and bending moments and shear of the girder. The maximum load effect values for each daily vehicle load WIM measurement data were then recapitulated, and the type of variable distribution was sought using the distribution fitting method for the purpose of reliability analysis. Using extreme value theory, the mean maximum load effect for a 75-year return period (corresponding to the bridge's design service life) was calculated, as seen on Figure 5. The mean maximum for 75-year return period value then can be used for reliability analysis to assess the long-term safety and performance of the Youtefa Bridge.

Figure 5 displays the load effect data in the form of axial force on the steel Arch member of Youtefa bridge as an example due to moving load analysis using one-year WIM load measurement data. The scattered black dots represent the data, which were then fitted by a distribution fitting method. The Gumbel distribution was found to be the most suitable distribution for the data, which is represented as a striped curve on top of the scattered dots (load effect data). Using extreme value theory, the Gumbel distribution type I curve was projected for a 75-year return period. As a result, the distribution for the 75-year return period can be determined, as well as its mean maxima to be used in the reliability analysis.

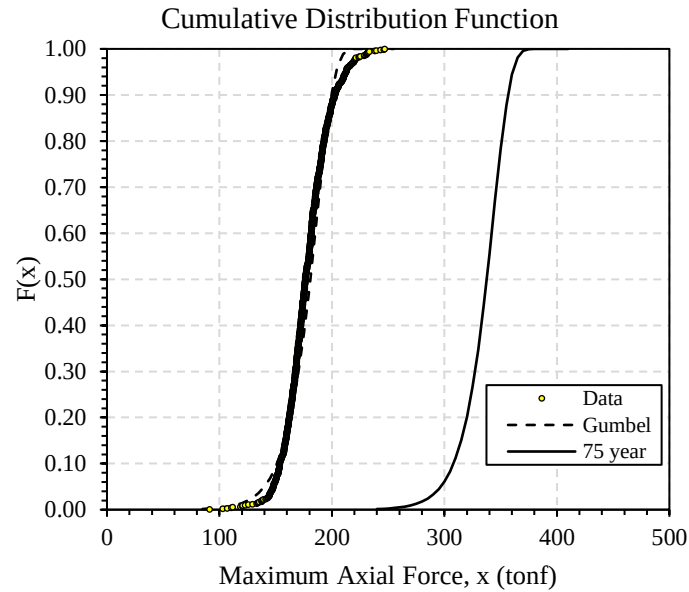


Figure 5 CDF of Maximum axial force and its 75 year projection

Reliability analysis

Reliability analysis is a critical aspect of bridge design, construction, and maintenance. It involves the evaluation of the performance of the bridge over time under the influence of various loads and environmental conditions. The reliability analysis of the Youtefa Bridge was conducted to ensure the safety and reliability of the bridge over its lifespan. The use of WIM data in this research is an innovative approach that provides detailed information about the traffic loadings on the bridge and it is essential for the design and construction of bridges, as it provides a more accurate representation of the traffic loads on the bridge. The analysis involved the calculation of the reliability index of the bridge using the load effect obtained from the WIM data. The reliability index is a measure of the bridge's ability to withstand loads over its lifespan, and it is used to assess the safety and reliability of the bridge.

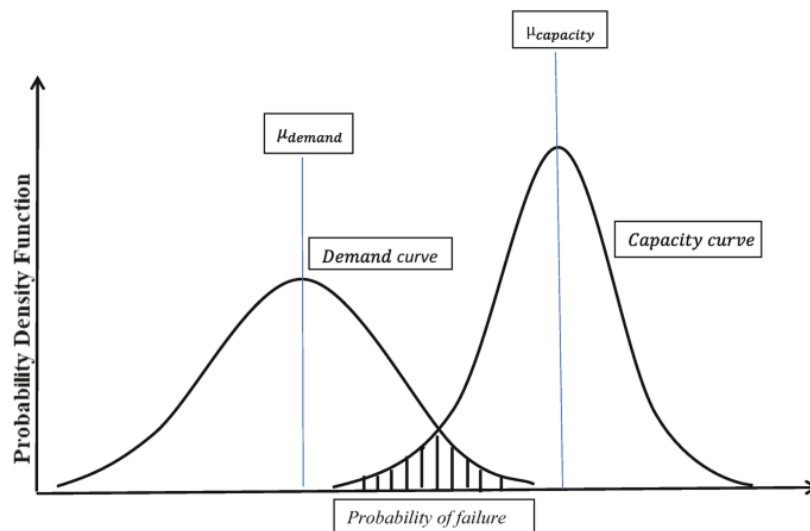


Figure 6 Reliability analysis concept (Putcha, Dutta, and Gupta 2021)

Reliability is the opposite of probability failure, which is represented as $1 - p_f$. Probability failure refers to the region of the probability density function where the capacity, as a random variable with its distribution curve, is lower than the demand, as a random variable with its distribution curve (Putcha, Dutta, and Gupta 2021). Figure 6 illustrates the concept of reliability, where the overlapping region of the two distributions is the probability of failure. Therefore, to calculate the reliability of a structure,

statistical data for both capacity and demand of the structure are required. In this study, the demand is the load effect for the 75-year return period due to WIM vehicle loading simulation on the Youtefa bridge model, and the capacity was derived from the sectional properties of each respective structural member of the Youtefa bridge.

The reliability analysis in this study used a combination of the First Order Reliability Method (FORM) (Ang and Tang 1975) and the Rosenblatt transformation (Rosenblatt 1952) to estimate the probability of failure of the Youtefa Bridge based on the input variables of the limit state function. The use of FORM allowed for a probabilistic assessment of the bridge's reliability, while the Rosenblatt transformation enabled the transformation of non-normal input variables into standard normal variables to preserve their correlation and ensure reliable results. FORM is a widely used reliability analysis method that estimates the probability of failure of a structure based on a performance function and the probability distribution of its input variables. The performance function in this study was defined as the difference between the capacity of each structural member and the maximum load effect.

To perform the reliability analysis, the input variables of the performance state function, including the capacity and demand, were assumed to be independent and normally distributed. However, the input variables were not completely followed normal distribution in the original form. In this study, the daily maximum load effect, which represents one of the demand functions, follows a Gumbel Type I distribution. This distribution was obtained by fitting the data for each respective structural member, as depicted on Figure 5 for steel arch member. On the other hand, the dead load effect was assumed to follow a normal distribution (Iatsko and Nowak 2021). The resistance, which represents the capacity function, was calculated for each respective structural member by taking into account its bias factor and coefficient of variation. The resistance was assumed to follow a lognormal distribution (Iatsko and Nowak 2021), and this was used in the reliability analysis. Therefore, the Rosenblatt transformation was used to transform the input variables into standard normal variables. The Rosenblatt transformation is a method that transforms non-normal input variables into standard normal variables by using their marginal distributions. This transformation preserves the correlation between the input variables and ensures that the transformed variables are standard normally distributed. The transformed variables were then used as inputs for the FORM analysis to estimate the probability of failure of the structural members.

Table 2 Iteration on reliability analysis of steel arch member of Youtefa bridge

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	757.87	5851.72	0.570	0.0039	100.59	877.70	740.05	5785.89	4.154
2	787.09	2204.28	0.735	0.0029	166.73	330.62	884.68	4331.60	5.367
3	1263.76	2840.98	0.970	0.0002	267.70	426.12	714.35	4861.88	5.403
4	1458.12	2977.33	0.984	0.0001	308.87	446.57	578.07	4955.65	5.443
5	1506.71	3014.44	0.988	0.0000	319.16	452.14	539.05	4980.07	5.457
6	1515.47	3020.56	0.989	0.0000	321.02	453.05	531.82	4984.06	5.460
7	1517.06	3021.70	0.989	0.0000	321.36	453.22	530.50	4984.80	5.460
8	1517.34	3021.89	0.989	0.0000	321.41	453.25	530.27	4984.92	5.460
9	1517.38	3021.93	0.989	0.0000	321.42	453.26	530.23	4984.95	5.460
10	1517.39	3021.94	0.989	0.0000	321.43	453.26	530.22	4984.95	5.460

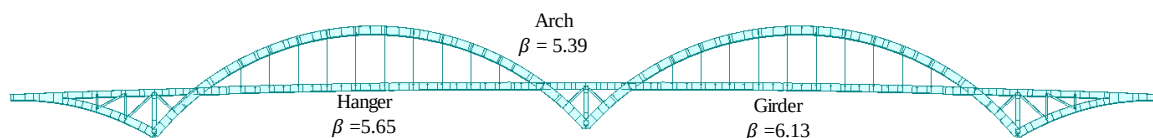


Figure 7 Reliability analysis result for each structural member of Youtefa bridge

Table 2 presents an example of the calculation of the reliability index for a steel arch member using FORM and Rosenblatt transformation. The reliability index results for all structural members, including hangers and girders, are depicted in Figure 7. The steel arch member has the lowest reliability index among the three structural members calculated in this study, with a value of 5.39. Therefore, as the defining member, the reliability index of the Youtefa Bridge is 5.39.

The obtained reliability index of Youtefa bridge, which is 5.39, indicates that the bridge is highly reliable and safe for the expected traffic loads. However, it is interesting to note that the reliability index is higher than the target reliability of bridges in Indonesia, which is 3.72. This suggests that the Youtefa bridge has a significant margin of safety against the target reliability, indicating that the design of the bridge is robust and able to withstand extreme loading conditions.

Furthermore, the results of the reliability analysis can be used to optimize the maintenance and inspection strategies for the Youtefa bridge. By identifying the structural members with the lowest reliability index, such as the steel arch member in this study, maintenance and inspections can be focused on these areas to ensure the continued safe operation of the bridge. Additionally, the results can inform future designs of similar bridges by providing insight into the structural behavior under real-world loading conditions and identifying areas for improvement.

Overall, the reliability analysis conducted in this study provides a comprehensive understanding of the performance and safety of the Youtefa bridge. By incorporating statistical data and advanced analysis techniques, the study has demonstrated the importance of reliability analysis in evaluating the structural integrity of bridges and optimizing their maintenance and inspection strategies.

Conclusion

In conclusion, this study evaluates the performance of Youtefa Bridge using B-WIM data from the national road in Indonesia. By simulating the vehicle loads on the bridge, the load effects and capacities of the structural members were obtained. The reliability analysis was then conducted using FORM and Rosenblatt transformation. The results show that the steel arch member has the lowest reliability index of 5.39, which makes it the defining member for the bridge. The reliability index of Youtefa Bridge is 5.39, which is higher than the target reliability for bridges in Indonesia. This indicates that Youtefa Bridge is capable of accommodating the medium to heavy traffic load in Indonesia. However, it is important to note that regular maintenance and monitoring of the bridge is necessary to ensure its long-term reliability and safety. Overall, this study demonstrates the importance of using WIM data and reliability analysis in evaluating the performance of bridges under real-world traffic conditions.

For future research, it is suggested to consider the effects of environmental factors such as temperature and humidity on the reliability of the bridge. Moreover, the study can be extended by incorporating the dynamic behaviour of the bridge into the analysis, which may lead to more accurate reliability predictions. Additionally, the impact of aging and degradation of the bridge components on the reliability can be studied in more detail. Lastly, further studies can be conducted to compare the reliability of different bridges in Indonesia and identify factors that contribute to the differences in their reliability indices.

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