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LONG-TERM DEFLECTION OF PRESTRESSED CONCRETE BOX GIRDER BRIDGES DUE TO CREEP AND SHRINKAGE

Luki Hariando Purba[1], *Bambang Supriyadi[2] and Bambang Suhendro[3]

[1,2,3] Faculty of Engineering, Gadjah Mada University, Indonesia

*Corresponding Author, Received: 28 July 2022, Revised: 29 March. 2023, Accepted: 10 April 2023

ABSTRACT: Long-term deflection of the box girder prestressed concrete bridge is undoubtedly essential. Creep and shrinkage are significant influences on the long-term deflection. Some design code models do not consider the water-cement ratio as a creep and shrinkage parameter. The excess water-cement ratio will increase creep and shrinkage. B3 Model uses the water-cement ratio parameter to predict creep and shrinkage. This study examines the long-term deflection of the box girder balanced cantilever prestressed concrete bridge that already exists in Indonesia. The method used B3 Model creep and shrinkage prediction to input to the software and used Midas Civil 22 v1.2 software to model the Bridge and the result is compared to other models. The results of this study indicate that the behavior of the B3 Model predicts deflection more significantly than other models. The slope graph of the deflection shows that there is still an increase in deflection after 30 years. It means that moisture loss in the prestressed concrete bridge still occurs after 30 years. From the results, it can conclude that the water-cement ratio is an essential parameter for creep and shrinkage. Prediction of long-term deflection in this B3 Model is extreme but is still within the allowable deflection limit due to dead loads of ACI and CEB codes.

Keywords: Creep, Shrinkage, Deflection, B3 Model, Long-term

1. INTRODUCTION

Box girder prestressed concrete bridges are the most commonly used in spans of 100-300 m, including in Indonesia, because of their structural and economic efficiency [16]. Creep and shrinkage are unavoidable behaviors in prestressed concrete bridges. Concrete affected by creep and shrinkage will decrease structural performance, increase deflection, and affect the stress distribution [13]. The most frequently used bridge construction method is the cast-in-place balanced cantilever method [4]. The balanced cantilever construction method makes the creep and shrinkage strain significant in bridges. Precast and cast-in-place are two ways to construct a balanced cantilever [4]. The cast-in-place method is usually the tendon stressing at an early concrete age [17]. The creep strain will be significant in the balanced cantilever method because the concrete stresses tendons early [18]. If the creep strain is significant, the deflection in the bridge will also be significant [7].

Several box girder prestressed concrete bridges have shown excessive deflection, including the Koror-Babeldaob Bridge in Palau [7], the Urado Bridge in Japan [7], and the Jiang Jin Bridge in China [16]. The bridge is experiencing excessive deflection due to various factors, and one of the causes is creep and shrinkage [4-8]. One of the causes of creep and shrinkage is the excessive water-cement ratio [6,7]. When prestressed concrete bridges are cast in place, the water content can usually not be controlled perfectly in the field; it can lead to an excessive cement-water ratio [7]. Prestressed concrete bridges depend on time influenced by concrete age, environmental conditions, and the water-cement ratio [11].

Creep and shrinkage behavior can be predicted with creep and shrinkage models. The ACI [1], AASHTO [2], CEB [12], and European [9] models are predictions that are often used in designs to consider creep and shrinkage. Some predictions of the creep and shrinkage models do not consider the water-cement ratio. The water-cement ratio is important in predicting creep and shrinkage [5-7]. B3 Model is a model that considers the water-cement ratio as a factor of creep [5]. Some of the models often used in designs to predict creep usually reach a maximum after 30 years [10]. The behavior of the B3 Model is different from other models. B3 Model shows creep behavior with infinite linear logarithm increase over 30 years [10]. Prediction this B3 Model has shown the same deflection behavior for 56 measured long-span bridges [10]. The prediction of the B3 Model is acceptable [1].

This paper examines the long-term deflection of one of the existing box girder-balanced cantilever bridges in Indonesia, with a total span of 300 m and a main span of 132.5 m. B3 Model was used to predict creep and shrinkage, and CEB, AASHTO, ACI, and European models were used for comparison. Long-term deflection predictions were studied for up to 100 years. The deflection during the construction of the balanced cantilever is neglected. Deflection is only presented after bridge closure (the end of construction).

2. RESEARCH SIGNIFICANCE

Long-term deflection can be predicted using prediction models such as ACI, CEB, AASHTO, European, JSCE, etc. However, those models underestimated a few long-term deflections measured on the existing bridges [7]. The long-term deflection of prestressed concrete bridges is still increasing after 30 years [7], however, those models have stopped predicting long-term deflection after 30 years. From the previous literature, B3 Model has shown the accurate prediction of the long-term deflection of prestressed concrete bridges and predicts the deflection after 30 to 100 years. Therefore, B3 Model is deserved to use in predicting long-term deflection.

3. LITERATURE REVIEW

3.1 Viscoelastic Material

Creep and shrinkage in concrete is a viscoelastic material behavior. Concrete is an elastic and viscous material. Two basic theories explaining viscoelastic materials are the Maxwell and Kelvin models. In Fig.1, it can be seen the models which depict a viscoelastic material. Maxwell Model is connecting the spring in series to the dashpot, while the Kelvin model is connecting the spring in parallel to the dashpot [4].

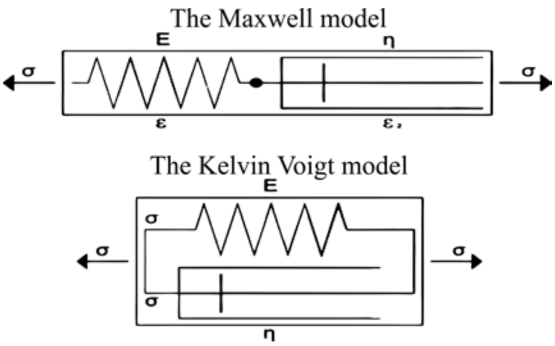

Fig.1 The Maxwell and Kelvin Voigt models [4]

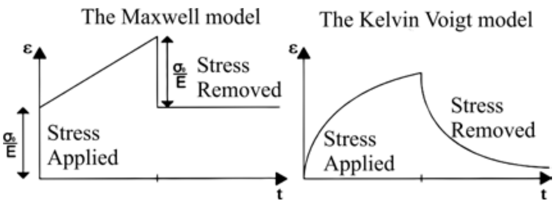

Fig.2 The Maxwell and Kelvin Voigt models strain due to constant stress [4]

In Fig.2, the graph shows the relationship between the strain and time of the Maxwell and the Kelvin models. In the Maxwell and Kelvin models, if given constant stress, there will be an elastic strain on the spring, and in the long term, the dashpot will strain from time to time due to that constant stress [14]. Strain in the dashpot is an additional strain on the elastic strain. This phenomenon is called the creep behavior of concrete. The difference between these two models is that the Maxwell model has linear elastic and viscosity strain while the Kelvin model is nonlinear. If the constant stress is removed, strain recovery in the Maxwell model does not occur, while the Kelvin recovery model gradually returns to zero.

3.2 Creep and Shrinkage Behavior

The design of a bridge requires an accurate prediction of the long-term behavior of the bridge [8]. Bridges generally have a service life of up to 100 years, so it is necessary to predict multi-decade creep and shrinkage models [8]. Creep and shrinkage have different behavior at an early age concrete and hardened concrete. The creep strain will be more significant if the concrete is stressed at an early age [3] and smaller if it is hardened concrete [15,18]. The shrinkage strain will be more significant if the curing of the concrete is stopped early and is smaller at hardened [15]. Creep and shrinkage in early-age concrete are more significant than that of hardened concrete because the modulus of elasticity in early-age concrete is still low, and the hydration process in concrete will result in a lot of water loss [3].

In this paper, the authors research the existing prestress concrete bridge in Indonesia. The construction method used is a balanced cantilever cast in situ. Each cantilever segment stresses the tendons after the concrete is three days old at the construction stage. Based on the above theory, the creep and shrinkage on this bridge will significantly affect the deflection.

Creep and shrinkage are affected by temperature, humidity, water-cement ratio, aggregate, and construction method [4-7]. At the balanced cantilever construction stage, each additional segment will be stressed when the concrete is still at an early age, and the Form Traveler load is applied above the box girder to increase the bending moment with each additional segment. A balanced cantilever, creep, and shrinkage in early concrete during construction will significantly affect the displacement [17]. Stressing and loading on early-age concrete is not a problem as long as the displacement and stress during construction do not exceed the permissible limit.

3.3 B3 Model Behavior

Several researchers have used the B3 Model to study the long-term deflection of prestressed concrete bridges [12-17]. The Koror-Babeldaob Bridge exhibits excessive deflection and collapses in its 19-year service life [7]. Multiple model prediction codes compared with measured deflections. In Fig.3, it can be seen that all models underestimate the measured deflection except the B3 set2 model. B3 set1 and B3 set2 models have differences. The B3 set1 model is data adjusted to the design, while the B3 set2 model is data adjusted to field measurements. There is a difference between the modulus of design and the modulus of elasticity of the truck loading test. The B3 set1 model graph shows a more significant behavior than the ACI, CEB, and JSCE code models, and the B3 set2 model graph shows conformity to the measured deflection. Then the graph continued to 60000 days (150 years), and the ACI, CEB, and JSCE models look asymptotic after 10000 days (30 years), but the B3 set1 and B3 set2 models still show a significant increase up to 150 years. Bazant [7] also shows the deflection prediction behavior of the B3 Model for the existing box girder bridges in Japan. The predictions of the B3 Model are compared with the predictions of the JRA (Japan Road Association) model and the measured deflection. Prediction B3 Model has good accuracy compared with measured data, so the B3 Model is suitable for research on prestressed concrete bridges.

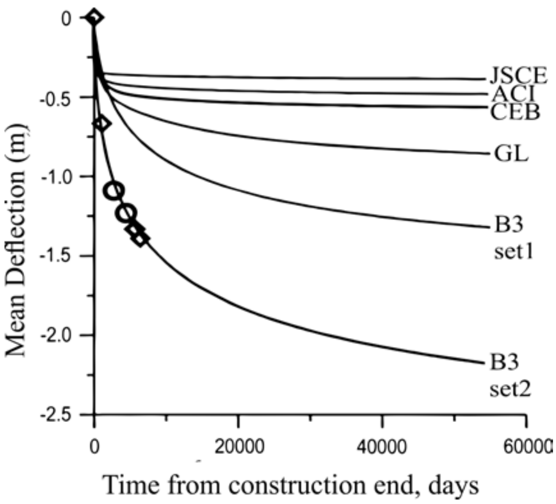

Fig.3 Deflection prediction with models and measured deflection Koror-Babeldaob Bridge [7]

Giaccu [15] compares the deflection graph of the box girder prestressed concrete bridge before and after retrofitting. Predictions of the B3 Model were compared against CEB 2010. Both models showed significant deflection at mid-span after two years. After ten years, both models still show the same deflection behavior. After ten years, the B3 Model still shows an increase in deflection behavior, while the CEB model is asymptotic, so the deflection increase is slight. After retrofitting, the deflection is reduced. B3 Model shows more significant predictive behavior than CEB 2010.

Elbadry [10] shows the graph comparing the creep coefficient of the B3 Model against CEB MC 2010. The 2010 CEB model is one design code that predicts creep more significantly than other codes. However, the B3 Model looks more significant than CEB 2010. The creep coefficient of CEB 2010 is asymptotic at 10000 days (30 years), while the creep coefficient of the B3 Model still shows a significant increase up to 125 years. This difference is quite significant where the B3 Model predicts a creep coefficient twice as significant as CEB 2010.

Several literature reviews that use B3 Model predictions conclude that the B3 Model significantly predicts creep and shrinkage. The slope of the B3 Model graph shows a significant increase over time. The other models seem to predict creep and shrinkage only up to 30 years, while the B3 Model still shows an increase. The water-cement ratio parameter is essential in predicting creep and shrinkage. ACI reported that the prediction of the B3 Model is acceptable and has shown conformity with experimental data in the RILEM Data Bank [1].

4. METHODOLOGY OF RESEARCH

Research on long-term deflection due to creep and shrinkage was carried out on one of Indonesia's existing balanced cantilever box girder prestressed concrete bridges. This bridge has a total span of 300 m with a main span of 132.5 m and a bridge width of 25.2 m. Pier P1 is 11.5 m, and pier P2 is 22 m. Fig.4, it can be seen that the total of all cantilever segments is 15 segments on the left and right sides. Stressing is done after each box girder segment is three days old. The compressive strength of the concrete on the upper structure is 38 MPa, and that of the lower structure is 35 MPa. The water-cement ratio used 0.4 and the humidity was 72%. This research utilizes Midas Civil 22 v1.2 software. The software already has a license from Midas IT. Bridge modeling is idealized with line elements, abutment placement as roller support, and pile cap placement as fixed support.

The idealization of balanced cantilever construction stages is using a construction stage analysis facility. The modulus of elasticity of each model's prediction is inputted into the software. Long-term compliance creep and shrinkage strain are inputted into Midas Civil software, and inputted time duration is 36500 days (100 years) with 2000-day intervals. During construction, the loads applied are dead loads, Form Traveler loads, wet concrete loads, and construction workers' loads. The calculated load in the long term is the structure's dead load, barrier, and asphalt.

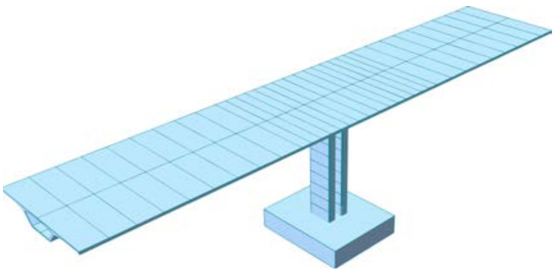

Fig.4 The 15-segment balanced cantilever

5. RESULT AND DISCUSSION

In Fig.9, the bridge's modeling after closure and construction completion can be seen. The creep and shrinkage models used are the B3 Model, CEB 2010, European, ACI, and AASHTO. Prediction of loss of prestressing is CEB 2010. This study only focuses on the effect of creep and shrinkage. The effect of creep and shrinkage on deflection is only focused on the main mid-span of the bridge. The results will be obtained in a bridge envelope displacement graph after 30 years, 100 years, and a deflection graph with time on the main mid-span until the 100-year bridge service life.

At the final stage of construction, the B3 Model, CEB, European, ACI, and AASHTO predict creep and shrinkage displacements of -46 mm, -31 mm, -31 mm, -37 mm, and -46 mm, respectively. All model predictions did not provide a significant difference. Displacement creep and shrinkage at the final stage of construction are calculated as bridge camber so that the bridge displacement becomes zero.

5.1 Deflection of B3 Model

In Fig.5, the graph of the deflection relationship to the time B3 Model can be seen. The graph of the deflection slope due to creep and shrinkage and the total deflection show the same behavior. If it is continued for up to 125 years, it may still show an increase in deflection due to creep as in the previous literature [7,10]. After 36500 days (100 years), the deflection due to creep is -144 mm, and the deflection due to creep and shrinkage is -156 mm. There is a slight additional deflection due to shrinkage. The total accumulated deflection due to creep, shrinkage, and loss of prestressing is -175 mm. The total accumulated deflection due to creep, shrinkage, and prestressing loss is -175 mm. The total deflection does not exceed the allowable limits of ACI codes L/240, and CEB L/250.

Fig.10 shows the displacement relationship to the x-axis coordinates along the bridge. In Fig.10 (a) it can be seen that the displacement of the bridge B3 Model is due to creep, creep with shrinkage accumulation, and the total after 30 years and 100 years after closure. Maximum displacement is in the middle of the main span. After 30 years, the total displacement reached -147 mm with a creep effect percentage of 81.24% and a creep and shrinkage effect of 89.32%. The maximum displacement of 30 years looks very significant. The creep and shrinkage effect is significant in the first 30 years of the bridge's service life due to the tendons' stress during cantilever construction when the concrete is three days old. Concrete aged three days or early concrete will have a significant creep and shrinkage impact because the cement paste hydration process and the modulus of elasticity have not been achieved. Stressing at an early concrete is not a problem because the stress and displacement at the construction stage do not exceed the applicable code permit limits. Fig.10 (b) is the displacement after 100 years, and the total displacement in the middle of the span is -175 mm, with a creep effect percentage of 82.23% and a creep and shrinkage effect of 89%. The most affecting deflection is a creep. The increase in displacement from the initial closure to 30 years is substantial, while the displacement from 30 years to 100 years is already tiny. The results of the displacement B3 Model still show an increase in displacement due to creep after 30 years, which is to the previous literature. B3 Model shows an increase in creep with a linear logarithm of infinite time[7].

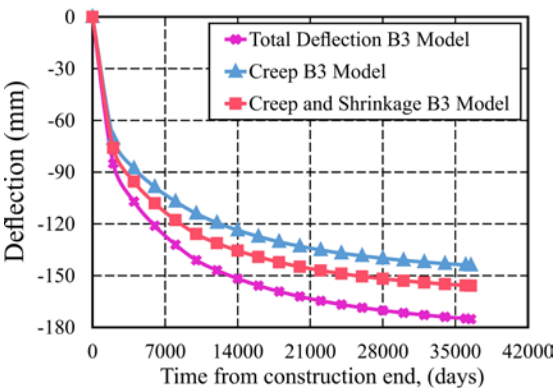

Fig.5 Deflection B3 Model with time

5.2 Comparison of B3 Model Deflection with Model Variations

In Fig.6, it can be seen the comparison deflection creep B3 Model with another model. The creep effect deflection is 63% to 87% for each model. B3 Model predicts creep deflection of -144 mm, while the CEB 2010, European, ACI, and AASHTO models are -100 mm, -95 mm, -85 mm, and -77 mm, respectively. The creep deflection of the B3 Model is 44% to 87% greater than the other models. In Fig.7, the graph comparing the deflection due to creep and shrinkage of the B3 Model to other models can be seen. B3 Model predicts deflection due to creep and shrinkage of -156 mm, while the CEB 2010, European, ACI, and AASHTO models are -115 mm, -105 mm, 89 mm, and -93 mm, respectively. The predicted deflection due to creep and shrinkage of the B3 Model is 35% to 75% more significant than the other models. Creep and shrinkage affect total deflection by 81% to 89% for each model's prediction. In Fig.8 can be seen the total deflection of the bridge. Creep and shrinkage show the most influential behavior on the total deflection. The total deflection of the B3 Model is 31% to 72% more significant than the other models. This difference indicates that the effect of the creep and shrinkage B3 Model on deflection is more significant than the other models.

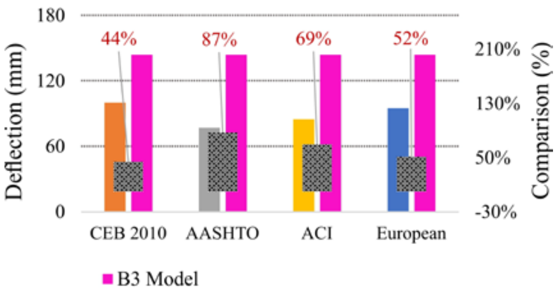

Fig.6 Comparison of the deflection due to creep of the B3 Model to the other models

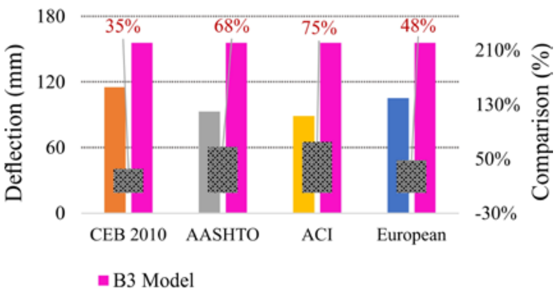

Fig.7 Comparison of the deflection due to creep and shrinkage of the B3 Model to the other models

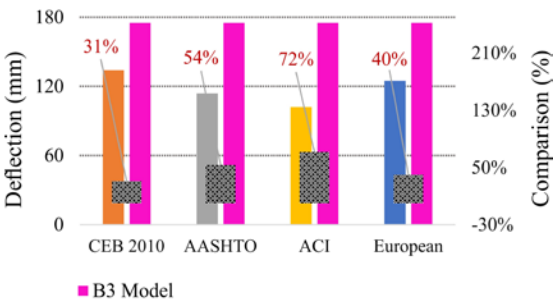

Fig.8 Comparison of the total deflection B3 Model to the other models

In Fig.11 (a), the graph of the deflection relationship due to creep with time can be seen. The graph of the deflection caused by creep is presented for up to 36500 days (100 years). All graphs of each model show the same linear behavior up to 2000 days (5.5 years), and after that, all graphs show different behavior. The CEB 2010, European, ACI, and AASHTO models show asymptotic deflection after 4000 days (11 years), while the B3 Model still shows deflection with a significant increase. It can be seen from the slope that the B3 Model still shows a significant graphic behavior compared to other models, which have shown asymptotic behavior where the increase in creep deflection has decreased over time. Prediction of the B3 Model shows that the modulus of elasticity of concrete still decreases due to creep up to 100 years of bridge service life while other models are the opposite.

In Fig.11 (b), the graph of the deflection relationship due to creep and shrinkage with time can be seen. Creep and shrinkage affect deflection very significantly. The slope of the deflection graph B3 Model due to creep and shrinkage shows a significant increase in deflection behavior over time, while the other models show an asymptotic slope so that the deflection increase is slight over time. Deflection due to creep and shrinkage increases linearly after 4000 days (11 years) of bridge service life. In the early stages, the creep and shrinkage increased significantly because the stressing of each segment was carried out on early concrete. Creep and shrinkage in early concrete will increase faster than in hardened concrete. B3 Model still shows an increase in creep and shrinkage deflection after 10000 days (30 years) to 36500 days (100 years), while the other models appear asymptotic. It means that creep and shrinkage still occur after 30 years on the bridge.

In Fig. 11(c), it can be seen that the total deflection is the accumulation of creep, shrinkage, and loss of prestress. The total deflection of all models showed the same behavior after 4000 days (11 years). The behavior of the total deflection graph is almost identical to the creep and shrinkage deflection graph, which means that creep and shrinkage are the most influential in long-term deflection. Up to 100 years, the total deflection B3 Model graph shows more significant predictions than other models. The total deflection of the B3 Model is -175 mm, while the CEB 2010, European, ACI, and AASHTO models are -134 mm, -125 mm, -102 mm, and -114 mm, respectively. All models predict long-term deflections not exceeding the allowable deflection limits due to dead loads ACI L/240 and CEB L/250, including B3 Model.

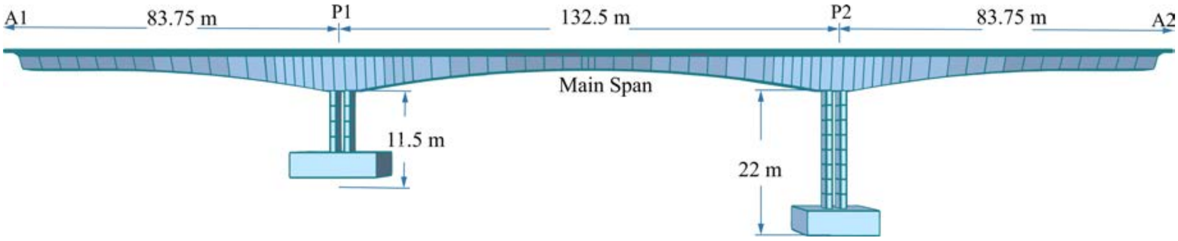

Fig.9 Bridge modeling after closure in Midas Civil software

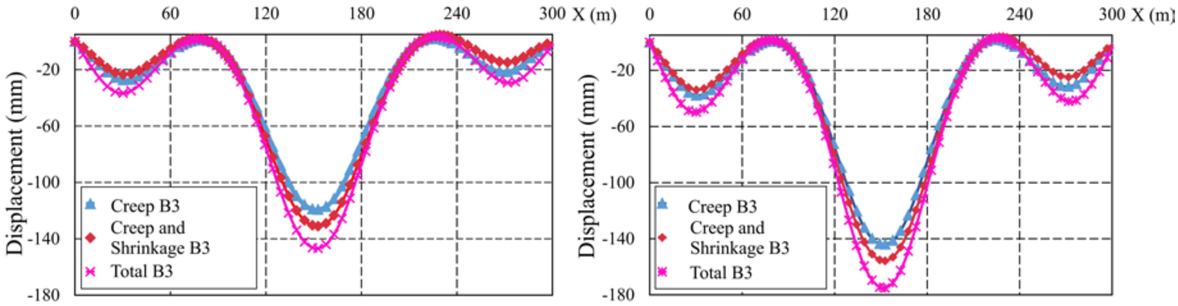

Fig.10 (a) Displacement after 30 years and (b) displacement after 100 years due to creep and shrinkage

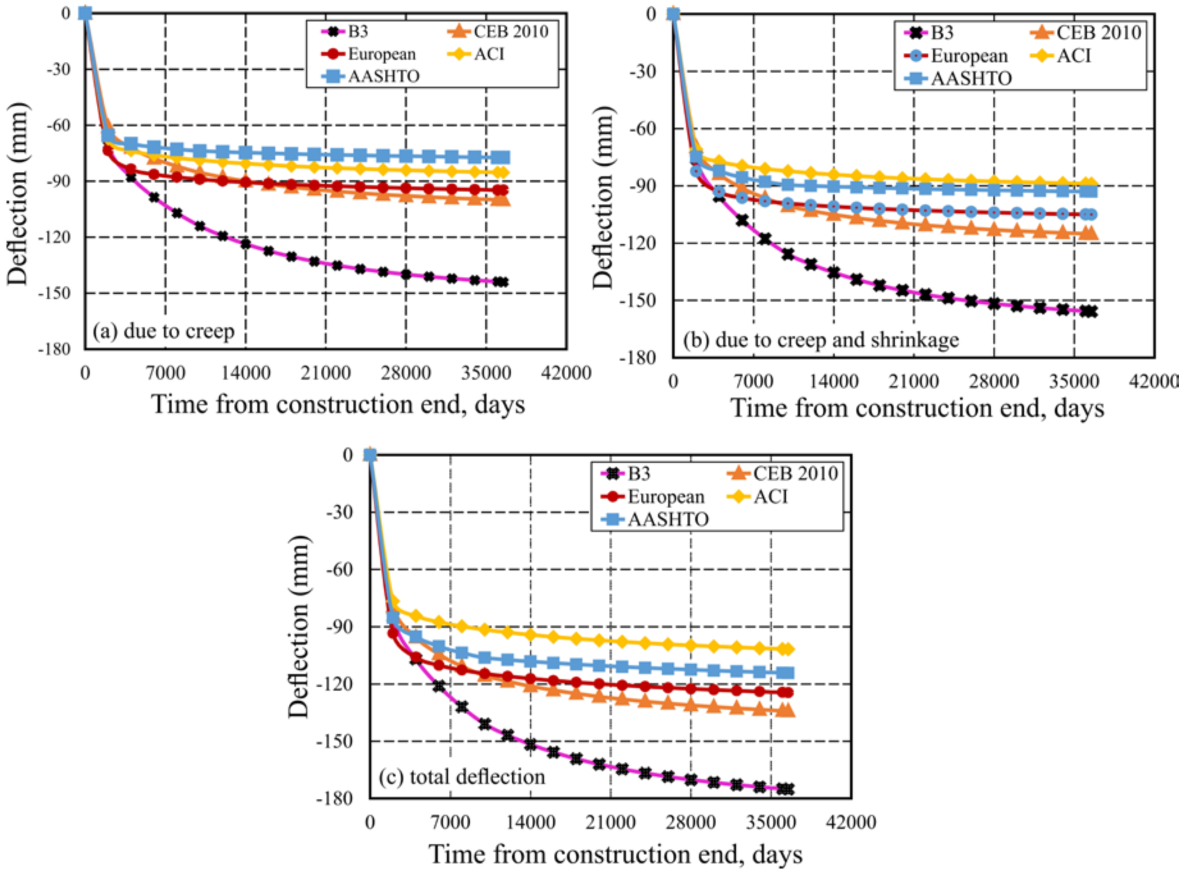

Fig.11 Comparison graph of deflection with time (a) due to creep, (b) due to creep and shrinkage, and (c) total deflection

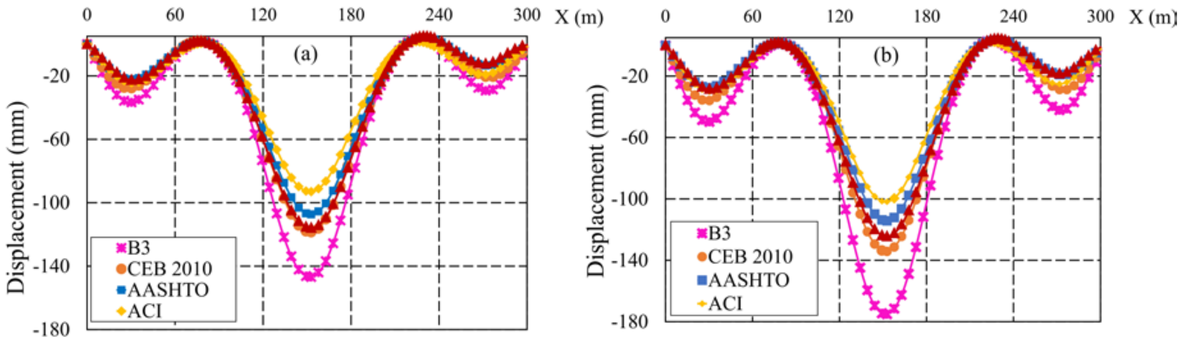

Fig.12 Comparison of variations in the envelope displacement model of the bridge (a) 30 years and (b) 100 years after the end of construction

In the previous literature, it can be seen that the design model underestimates the measured data. It may be why Bazant [7] developed the creep and shrinkage prediction of the B3 Model and proved to be under the measured data in the field. The possible reason is that the water-cement ratio plays an essential role in creep and shrinkage. The B3 Model predicts that moisture loss will still occur for up to 100 years, so the deflection increase due to creep and shrinkage on the bridge will still occur. The evidence is that the measured deflections of bridges in Japan and Palau show excessive deflections over 30-100 years [7]. That means that the deflection due to creep and shrinkage is still going on for up to 100 years.

Furthermore, this model's long-term B3 Model deflection prediction seems unrealistic because it has exceeded the allowable limit in the previous literature. However, in this study, the B3 Model deflection prediction did not exceed the permissible limit, which means that the long-term deflection prediction is acceptable. The difference is because the prediction of prestress loss on the Koror-Babeldaob Bridge in Palau is very extreme, reaching 50%, while in this study, it was approximately 20%. ACI [1] also commented that the B3 prediction of this model is acceptable because it has good accuracy on the measured data provided by the RILEM Data Bank. B3 deflection prediction This model is unique because it is different from the popular code design model.

In Fig.12 it can be seen a comparison of the predictions of the envelope displacement bridge model. Fig.12 (a) displacement of 30 years of service life of the bridge and (b) displacement of 100 years of service life of the bridge. The left side span (A1-P1) and right side span (A2-P2) also experience deflection in addition to the middle span (P1-P2). All models predict maximum displacement in the bridge's middle of the main span. Displacement prediction B3 Model on all bridge spans shows more significant behavior than other models. All models predict that the total displacement of all spans does not exceed the allowable limit due to ACI L/240 and CEB L/250 dead loads. It means that the existing bridge in Indonesia will remain stable and safe for up to 100 years or the end of the bridge's service life.

6. CONCLUSIONS

Creep and shrinkage in prestressed concrete bridges are unavoidable. The influence of the construction method will affect the creep and shrinkage of the prestressed concrete bridge. The maximum displacement is in the main span of the bridge. In this study, the effect of creep and shrinkage on long-term deflection reached 81% to 89%. The total deflection of the B3 Model is 31% to 72% more significant than the other models. B3 Model shows that moisture loss in the concrete still occurs after 30 years, so the deflection due to creep and shrinkage still increases after 30 years. Therefore, the B3 Model parameter of this model is based on the water-cement ratio, while the other model is the opposite [5].

B3 Model predicts deflection of 100 years of bridge service life significant in the long-term; however, it is still within the allowable deflection limit due to dead load code ACI L/240 and CEB L/250. These results can be concluded that the B3 Model predicts the deflection realistically because it does not predict exceeding the applicable code permit limits, so the authors agree with ACI's comment [1] that the B3 Model deflection prediction is acceptable.

7. ACKNOWLEDGMENTS

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