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A Simplified method to minimize exterior girder rotation of steel bridges during deck construction

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ABSTRACT

Wide flange beams are widely used in the United States for bridge design and construction. During the overhang construction of the bridge, torsional loads are often induced due to the fresh concrete load and the use of a deck finishing machine located on the overhang formwork. These torsional moments sometimes cause excessive exterior girder rotation, resulting in many safety and maintenance issues during the construction and service stages. To prevent these issues, most states have specifications for limiting the rotation. Finite element analysis using shell or solid elements is usually recommended for analyzing bridge girders in overhang construction, which can be tedious and difficult in some cases. This study focused on developing a simple method with minimal calculation to evaluate the ratio of unbraced length to girder depth (B/D ratio). The stepwise variable selection method and a regression analysis were conducted to find the relationship between the exterior girder rotation and bridge geometries. A computer program for automatic finite element modeling in SAP2000 was developed using MATLAB, resulting in 4285 finite element models with different bridge geometries being developed to generate artificial data. By conducting a study of variable selection, three parameters were selected based on level of significance. After conducting a regression analysis based on the selected parameters, a method using the normal weight of girder, overhang width, and rotation limit to determine B/D ratio was developed.

1. Introduction

In the U.S., wide flange beams are commonly used as supports for a bridge deck slab and traffic loads. Typically, these wide flange beams are uniformly spaced transversely, with the bridge deck overhang cantilevering past the exterior girder. The construction of the deck overhang often requires utilizing overhang brackets to support the fresh concrete, deck finishing machine, and other construction loads. As shown in Fig. 1, deck overhang brackets are generally connected to the top flange and react against the bottom of the exterior girders' web, with spacings between 0.9 m (3ft) to 1.2 m (4ft) along the exterior girders [1,2]. The deck finishing machine, generally located on the edge of the overhang, creates significant loads on the bridge's exterior girders during deck construction (Fig. 2).

One of the major issues in deck construction is unbalanced loads applied along the overhang portion of the deck slab, mostly due to the weight of the deck finishing machine and fresh concrete [3–5]. During deck construction, the bridge shows less transverse stiffness since the concrete deck slab has yet to provide stiffness to the structure. Also, the construction loads are transferred through the overhang bracket formwork system to the exterior girder, causing significant torsional moments on the exterior girder. These torsional moments can lead to excessive transverse rotation of the exterior girder, and instigate many safety and maintenance issues during both the construction and service stage of the bridge, such as changes in deck thickness [3,6], local and global instabilities [7–10], and potential bridge failure [11–13]. Therefore, AASHTO LRFD Bridge Design Specification (2012) [14] requires that the effect of reactions from the overhang brackets be considered during bridge design, and recommends using a three-dimensional (3-D) finite element analysis using shell or solid elements for the torsional analysis in order to recognize the warping effects. The Guidelines for Steel Girder Bridge Analysis (2011) [15] introduces a method using the equivalent torsional constant, which includes the St. Venant torsional stiffness and warping fixity at each end of a given unbraced length, to determine the rotation of the girders.

To prevent these issues, most of the departments of transportation (DOT) in the United States have specified a maximum allowable overhang width to reduce the torsional moments based on the bridge geometries, such as girder spacing, girder depth, or deck thickness [16–20]. Some states also specify a maximum allowable rotation for the exterior

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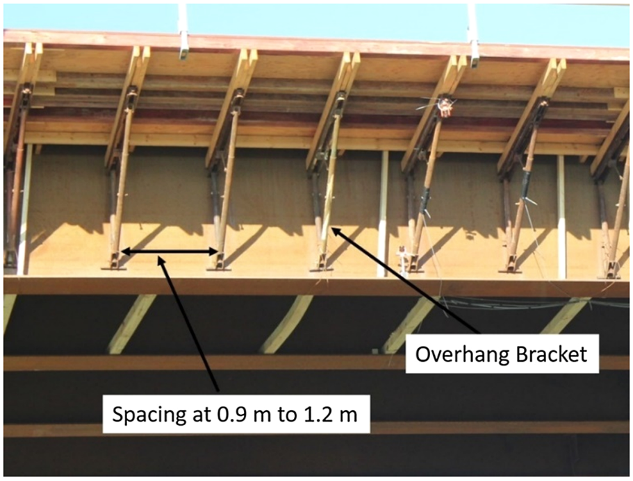


Fig. 1. Overhang bracket for deck construction.

girder during deck construction. The state of Illinois stipulates a maximum exterior girder rotation according to the maximum overhang deflection [20]. Kansas DOT requires the maximum exterior girder rotation to be less than one degree, and that the overhang width should be determined based on the torsional loads acting on the exterior girder, which is determined using the Torsional Analysis for Exterior Girders (TAEG) software [21,22]. However, this software has some limitations in computing the exterior girder rotation [23].

Another common effective method to reduce the exterior girder rotation is to add permanent and temporary lateral bracing systems into the bridge. The permanent bracing systems, such as diaphragms and cross-frames, are typically designed to resist the lateral loads during the service stages, without considering torsional moments generated from construction loads [3,24]. Therefore, temporary bracing systems are usually employed during bridge deck construction to prevent excessive rotation of the exterior girder [3,25]. However, those temporary bracing systems are generally implemented without detailed analysis, diminishing their effectiveness [3,11].

This research focused on developing a simple method to determine the unbraced length of the bridge for limiting the exterior girder rotation. A study of variable selection based on the stepwise selection method [26–28] was conducted in order to find the significances of bridge parameters that can affect the exterior rotation and their interaction with each other. The normal weight of the girder, the overhang width, and the ratio of unbraced length to girder depth (B/D ratio) were selected as the most effective indicators to predict exterior girder rotation. A total of 4285 finite element models were built according to the current bridge design and construction practice in the USA, which typically uses standard wide flange I-beams as main girders and the concrete deck is cast for the full width of the bridge using the screed machine. A regression analysis was also implemented to find the relationship amongst the selected parameters. Finally, a simplified method, using the normal weight of wide flange beam, overhang width and the allowable exterior girder rotation, to determine the unbraced length of bracing systems was developed based on the results of the regression analysis. This simplified method can be used as a rapid tool to determine the B/D ratio for straight bridges with no skew or minor skew in order to limit the exterior girder rotation during the bridge deck construction.

2. Finite element modeling and artificial data generating

2.1. Preliminary parameters consideration

During the overhang construction of bridges, the exterior girder rotation can be affected by the loading conditions, material properties, and bridge geometries. Bridge deck construction often utilizes a screed machine to remove excess concrete, and produce a smooth, uniform deck surface. Typically, the wheels of the screed machine are located on the edge of the overhang formwork, inducing torsional moments on the exterior girder. For this study, the Bidwell-3600 screed machine (Terex Co., Canton, SD, USA), a conventional model used in bridge deck construction, was used. The loads generated by the screed machine were simplified as four concentrated loads of 3336.2 N (750 lb) at each wheel on the sides of the bridge (Fig. 3). The thickness of the concrete deck slab was assumed to be a consistent 20 cm (8 in) based on the design specifications ([14,20]). Since the concrete deck cannot provide stiffness for the bridge during deck construction, the weight of the fresh concrete was simplified as loads distributed along the bridge girders in this study, with a unit weight of 23.56 kN/m^3 (150 lb/ft^3). Additionally, the elastic modulus of steel was assumed to be 200 GPa (29,000 ksi).

Since the loading conditions and material properties were considered constant, the bridge geometries were the main factors that affected the exterior girder rotation. As shown in Table 1, the girder section, span length, girder spacing, overhang width, number of girders, and diaphragm sections were selected as preliminary parameters that had the possibility of impacting the exterior girder rotation during overhang construction. A total of 93 sections from the AISC section database [29] were selected for the bridge girders, ranging from W27 to W44. The minimum span length was chosen as 9.14 m (30 ft), which included three diaphragms with a minimum spacing of 3 m (10 ft), as specified in the Illinois Bridge Manual [20]. The maximum span length varied based on the depth of the girder, which is taken as thirty times the girder depth [14]. The range for the overhang length was selected to be 36.6 cm (14.5 in) to 118.9 cm (46.8 in) based on the Illinois Bridge Manual, which states that the maximum value for the overhang length is half the girder spacing [20]. It also recommended that the minimum depth for the diaphragms equal half of the girder depth. Thus, W12 to W21 were selected for the diaphragm section [20]. Other parameters, such as girder spacing and number of girders, were chosen according to general design practices.

2.2. Finite element model

To find the significance of the preliminary parameters, the finite element method was used to generate artificial data for variable selection, as well as a regression analysis. The finite element models were established using SAP2000 [30], and validated in the previous study [3]. Fig. 4 shows a general finite element model used for artificial data generation. The bridges were modeled as simply-supported, with multiple girders laterally braced using diaphragms. The girders and diaphragms were modeled using shell elements with a mesh size of 2.54 cm (1 in) in order to include the warping effect. A three-dimensional frame element was used for modeling the overhang brackets and screed machine rails. The brackets were connected to the top flange of the exterior girder through common nodes, reacting against the web. The screed machine rails were built a distance, the overhang width, away from the exterior girder. The mesh size for the brackets and screed rails were also 2.54 cm (1 in).

As shown in Fig. 5, the construction loads applied to the finite element models were simplified as concentrated loads, representing the fresh concrete and screed machine. The weight of the fresh concrete between two girders, and on the top of the girder flanges, was simplified as concentrated loads acting at the edge and center of the top flanges since the formwork was supported by the hangers which connected the top flanges of girders to the form lumbers and were not able to transfer moment to the girder system. The forces from the fresh concrete on the deck overhang and the screed machine were modeled as vertical loads acting on the bracket. Since the top tie rods of brackets were connected to the top of girder flanges, and the inclined legs reacted against the girder web, the forces were transferred to the exterior girder, resulting in torsional moments that created rotation along the

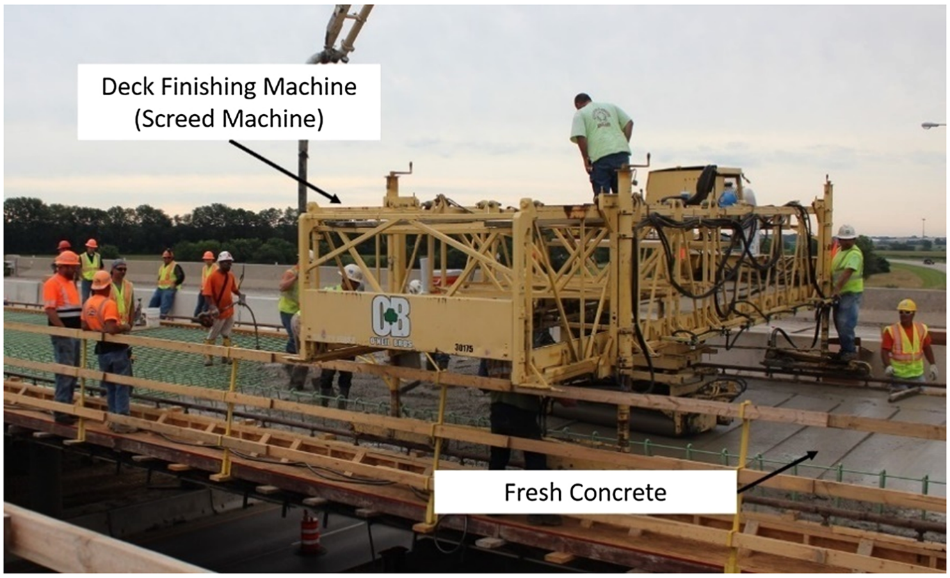


Fig. 2. Deck finishing machine (screed machine).

Fig. 3. Screed machine wheel load.

Table 1
Preliminary considered parameters.

Parameters	Variation Ranges					
Girder section	W27	W30	W33	W36	W40	W44
Span (m)	9–21	9–23	9–25	9–28	9–31	9–33
Girder spacing (cm)	183–305					
Overhang (cm)	36.6–118.9					
Number of girders	3–6					
Diaphragms	W12 to W21					
Slab thickness (cm)	20					
Concrete unit weight (kN/m^3)	23.56					
Elastic modulus of steel (GPa)	200					

girder. The maximum rotation in the exterior girder usually occurs at the middle of the span during the overhang construction [3]. Therefore, loads from the fresh concrete and screed machine were calculated based on the bridge geometries and the mesh size of the model, then applied to the nodes between the support and midspan. Only maximum rotation values were considered for estimating the relationships amongst all the parameters.

2.3. Data generation

To estimate the changes of all the parameters, more than 4000 finite element models were needed. Therefore, a computer program was developed in MATLAB [31] to automatically create finite element models and extract results. The computer program read bridge geometries from an input file: a list of bridges with information on the girder sections, span length, diaphragm spacing, girder spacing, overhang width, number of girders, and diaphragm sections. Then, the nodal coordinates, element information, material properties, section dimension and properties, and boundary conditions were computed and saved in the format of a SAP2000 input file. The API functions of SAP2000 [32], a set of commands or functions that can be used to interact with other programming languages, were used to send the input file to SAP2000 for the finite element analysis. The maximum rotation values were also extracted from SAP2000 and saved in MATLAB using the API function. When the program detected the end of the bridge list, the finite element analysis finished, and all the data, including the preliminary considered parameters and maximum rotation values, were saved for further analysis. Fig. 6 shows the calculation flow.

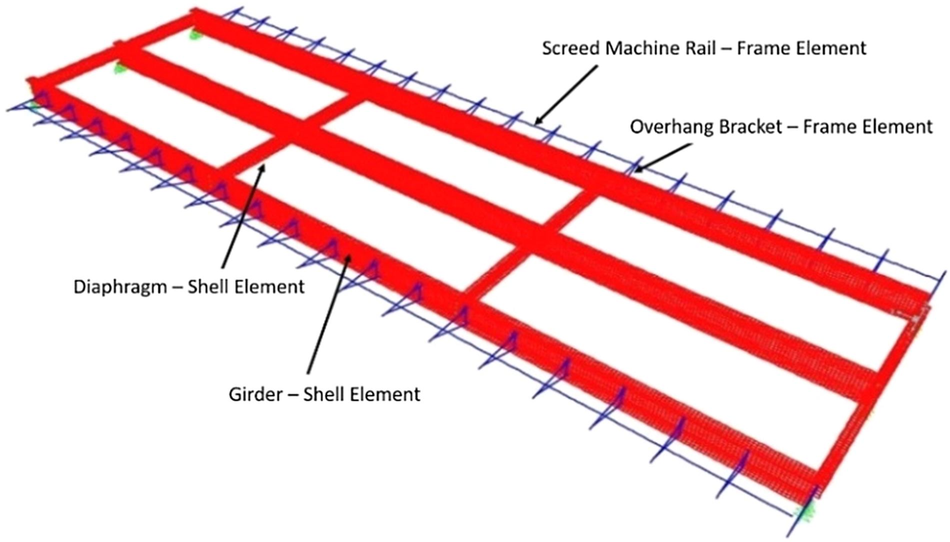


Fig. 4. Finite element model in SAP 2000.

A total of 4285 finite element models were developed using this computer program, and all the data, including the bridge parameters and maximum rotation values, were recorded. The girder and diaphragm sections were evaluated using two parameters, the depth and normal weight of the sections, neglecting detailed section properties such as the moment of inertia, torsional constant, and area. This is because, to some extent, the depth of the section and normal weight can represent the rigidity of the section in resisting external forces. The girder depth ranged from 68.6 cm (27 in) to 118.8 cm (44 in), while the normal weight changed from 125.1 kg/m (84 lb/ft) to 971.2 kg/m (652 lb/ft). For the girder depth, the mean value was 90.4 cm (35.6 in), while the median value was 91.4 cm (36 in). The values of the mean and median indicated the central tendency of the values, and can be used to judge the skewness of the dataset, while the standard deviation reflected the dispersion of the dataset. This indicated that the distribution of the girder depth was almost symmetrical since the values of the mean and median were similar. The ratios of the unbraced length to girder depth (B/D ratio) for each bridge configuration were also added to the dataset since the previous study showed that the B/D can be an effective, and efficient, indicator in evaluating the exterior girder rotation during deck construction [3]. The B/D ratio ranged from 2.7 to 11.1 with the same mean and median values (6.8). The properties of the other bridge parameters and the response variable (rotation) from the dataset are shown in Table 2.

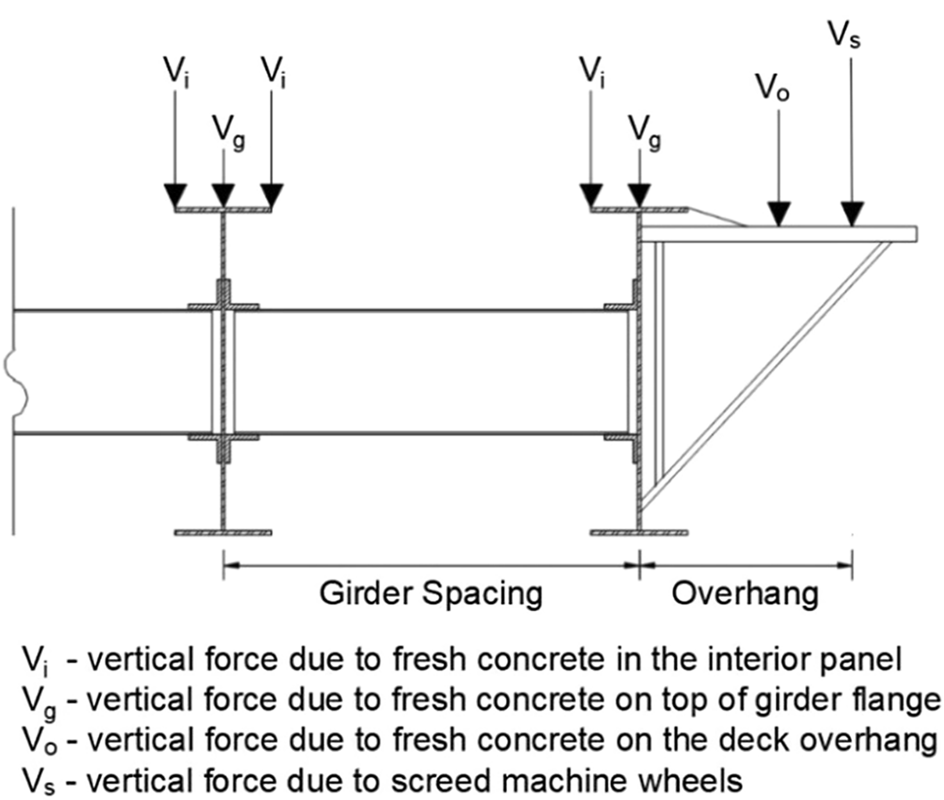


Fig. 5. Construction loads simplification.

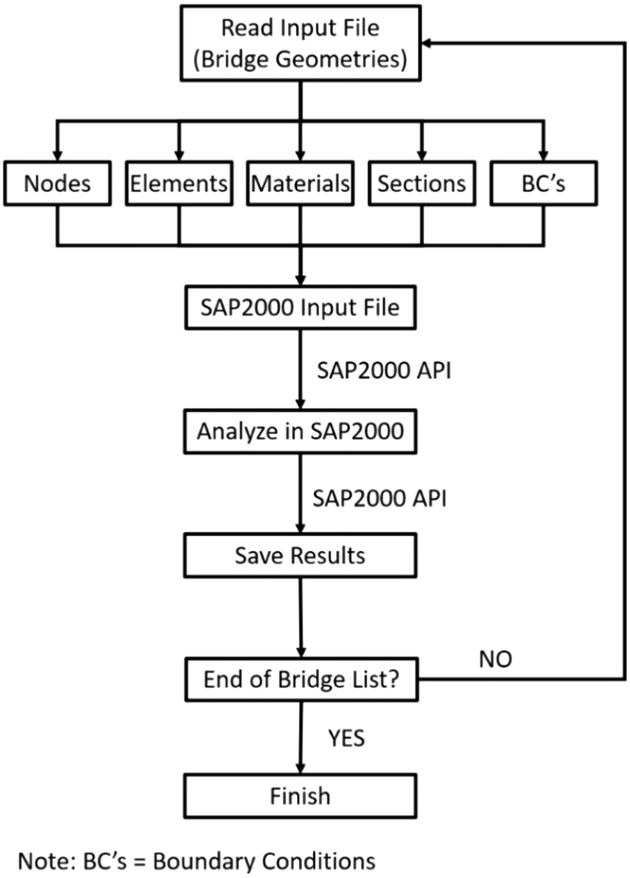


Fig. 6. Procedure for data generation.

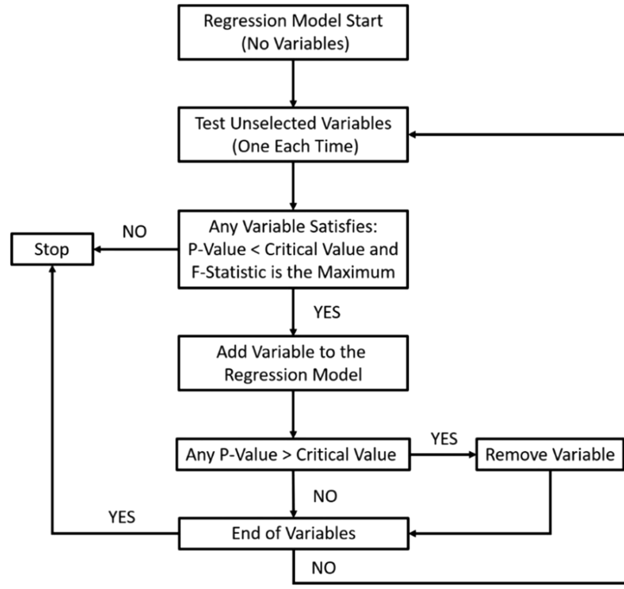


Fig. 7. Procedure for stepwise variable selection.

3. Variable selection and parametric study

3.1. Variable selection

The purpose of variable selection is to remove redundant predictors and find subsets of variables that produce an optimal regression model. These unnecessary predictors usually add noise to the estimation of other variables and result in collinearity of the variables and overfitting problems. Therefore, a study of variable selection is often conducted to evaluate the significance of each variable to find the smallest model that best fits the data.

The method of stepwise variable selection was used to find the significances among all the parameters. The stepwise selection is a method that allows adding, or removing, variables at various steps by testing critical values, such as F-Statistic, P-Value and R^2 [28]. This study utilized F-Statistic and P-Value as criterions in finding the significances of the variables, and the best subset that fits the regression model. The F-Statistics, often used to compare statistical models that have been fitted to a dataset, is a statistical value that indicates the overall significances of variables in a dataset using F-distribution under the null hypothesis. The P-Value shows the probability of variables for a given statistical model, and quantifies the statistical significances level. Generally, the criterion for the P-Value is selected to be 0.05 [28,33], and any variable that has a larger value than the criterion can be considered insignificant.

The procedure for stepwise selection is shown in Fig. 7. The regression model starts with no predictors, and each variable is added to the model separately to test the F-Statistic and P-Value. After all the variables are tested, the one with the largest F-Statistic and P-Value that satisfied the criterion is added to the model. Then, the model is refitted, and the statistically insignificant variables are removed. The selection stops when no remaining variable is significant at the critical level.

To consider possible non-linear relationships between the maximum rotation values and the bridge geometries, a logarithmic transformation of the rotation values was applied to the data. The logarithmic transformation is commonly used in data analysis to evaluate non-linear relationships, while still preserving the linear model. The logarithmic transformation also transforms highly skewed data into normally distributed data. The logarithmic transformation was only applied to the rotation values to keep the model simple and efficient. The regression model was assumed to be Eq. (1).

$$\ln(Rotation)\ 1 + (SPAN + NOG + UBL + GS + OW + W + D + DW + DD + B/D) \tag{1}$$

Table 2
Description of generated data.

Variable	Unit	Lower bound	Upper bound	Mean	Median	Standard deviation	Skewness
Girder depth (D)	cm	68.6	111.8	90.4	91.4	11.9	−0.26
Girder normal weight (W)	kg/m	125.1	971.2	376.5	359.0	159.5	0.33
Diaphragm depth (DD)	cm	25.4	55.9	43.9	45.7	8.4	−0.64
Diaphragm normal weight (DW)	kg/m	17.9	1087.3	85.8	81.9	40.1	0.29
Span (SPAN)	cm	914.4	2286.0	1753.1	1737.4	502.2	0.09
Number of girder (NOG)	–	3.0	6.0	4.5	4.0	1.5	1.00
Unbraced length (UBL)	cm	304.8	762.0	584.5	579.1	167.4	0.10
Girder spacing (GS)	cm	182.9	304.8	216.7	213.4	23.6	0.42
Overhang width (OW)	cm	36.6	118.9	77.2	91.4	24.1	−1.77
B/D ratio (B/D)	–	2.7	11.1	6.8	6.8	2.3	0.00
Rotation	degree	0.0084	4.3418	0.2893	0.1730	0.3693	0.94

Table 3
Results of stepwise variable selection in each step.

	Step							
	F-Statistic	P-Value	F-Statistic	P-Value	F-Statistic	P-Value	F-Statistic	P-Value
	1		2		3		4	
SPAN	642	0	3450	0	12,000	0	10,500	0
NOG	0	0	3510	0.21	5080	0	12,400	0
UBL	642	0	3450	0	12,000	0	10,500	0
GS	0	0	3510	0.21	5080	0	12,400	0
OW	1050	0	5080	0	–	–	–	–
W	3510	0	–	–	–	–	–	–
D	792	0	1820	0	3570	0	10,400	0
DW	10.9	0	1760	0.05	3400	0.005	9600	0
DD	307	0	1830	0	3580	0	10,300	0
B/D	1060	0	3490	0	12,400	0	–	–
R^2	0.513		0.753		0.918		0.918	
	5		6		7		8	
SPAN	10,500	0	10,500	0	10,500	0	–	–
NOG	12,400	0	–	–	–	–	–	–
B	10,500	0	10,500	0	–	–	–	–
GS	–	–	–	–	–	–	–	–
OW	–	–	–	–	–	–	–	–
W	–	–	–	–	–	–	–	–
D	10,400	0	10,400	0	8410	0.06	8410	0.06
DW	9600	0	9600	0	8440	0	–	–
DD	10,300	0	10,300	0	8400	0.96	8400	0.96
B/D	–	–	–	–	–	–	–	–
R^2	0.918		0.927		0.927		0.927	

Note: SPAN = span length, NOG = number of girders, B = unbraced length, GS = girder spacing, OW = overhang width, W = normal weight of girder, D = girder depth, DW = normal weight of diaphragm, DD = diaphragm depth, B/D = ratios of unbraced length to girder depth.

Table 3 shows the values of F-Statistics and P-Values in each step during the stepwise variable selection. No variable was included in the model for the first step, but the F-Statistics and P-Values were computed by adding each parameter into the model. The normal weight of the girder (W) was selected to be added into the model since it had the largest F-Statistic while having a P-Value that was under the criterion value (0.05). During each step, one parameter was added to the regression model, and the significances of all other variables were re-evaluated. After doing eight steps, no remaining variable was found to satisfy the criterion of P-Value. Therefore, the analysis stopped. The results showed that all the bridge parameters impacted the exterior girder rotation, except the depths of girders and diaphragms.

However, it is also important to note that the value of R^2, which measures how close the regression line fits the data, can also be used with the stepwise selection results to simplify the regression model. Fig. 8 shows the changes of R^2 in each step during the stepwise variable selection. The value of R^2 increased dramatically during the first three steps, then remained at 0.918 until step six when it increased to 0.927. This indicates that by adding a couple of variables, the regression model was only improved by less than 1%, which is neither efficient, nor economical. Therefore, the final parameters considered as significant in exterior girder rotation were the normal weight of the girder (W), overhang width (OW), and ratio of unbraced length to girder depth (B/D ratio).

3.2. Effects of parameters

The results from the variable selection can be verified by analyzing the data generated from finite element models. Fig. 9 shows the effects of all parameters on the exterior girder rotation. The parameters were normalized to a range from zero to one, and the changes in rotation were computed in order to have a better comparison amongst all the parameters. The number of girders, girder spacing, span length and normal weight of the diaphragm had very limited impact on the rotation values. The girder depth also had limited effect on exterior girder rotation due to that the torsional and warping constant of a section mainly depend on the dimensions of girder flanges. However, the overhang width, unbraced length, diaphragm depth, B/D ratio and normal weight of the girders showed significant effects on rotation. The unbraced length, which was not included in the results of the variable selection analysis, has a relationship with the B/D ratio since the B/D

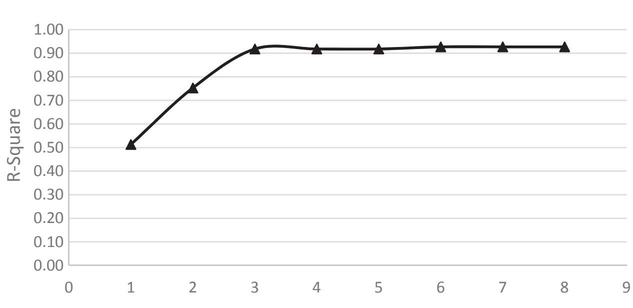


Fig. 8. Changes of R^2 in each variable selection step.

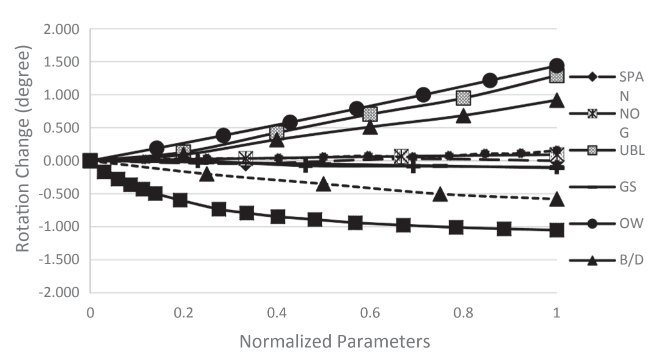


Fig. 9. Effects of parameters.

ratio was calculated directly from the girder depth and unbraced length. Therefore, the unbraced length was excluded from the regression model to simplify the model and avoid the overfitting problem.

The diaphragm depth also impacted the exterior girder rotation during deck construction. The rotation tended to decrease as the diaphragm depth increased [34]. However, the artificial data generated from the finite element analysis used the minimum requirement for diaphragm depth commonly applied in bridge design, resulting in a conservative evaluation. The effectiveness of the lateral bracing system on resisting the exterior girder rotation mainly depends on the effective depth of the system, regardless of the bracing type [34]. Therefore, the results from this study can also be used for other types of permanent, or temporary, lateral bracing systems.

4. Determine B/D ratio for overhang construction

4.1. Regression analysis

The study of variable selection indicated that only three parameters, the overhang width (OW), normal weight of the girder (W) and B/D ratio, needed to be included into the regression model. Three different models were created and evaluated to obtain the best regression results. Table 4 details each model. The linear model only considered the linear relationship between the three parameters and their corresponding y-intercept. The interaction model contained product combinations product pairs of the three predictors, the linear terms and y-intercept, while the quadratic model included the linear terms, interactions, squared terms, and y-intercept.

The linear model and interaction model had a similar R^2 (0.918 and 0.929, respectively), while the quadratic model was a better fit for the dataset, with R^2 equaling 0.969. Therefore, the quadratic model was selected for developing the method to determine the B/D ratio. Table 5 shows the estimate coefficients for each term in quadratic regression model. These coefficients were adjusted when the variables were introduced in the units of the International System. Also, based on the results of the quadratic model, the logarithmic transformed rotation values can be converted to rotation by using eq. (2).

$$Rotation = e^{f(OW,W,B/D)} \tag{2}$$

4.2. Determine maximum B/D ratio

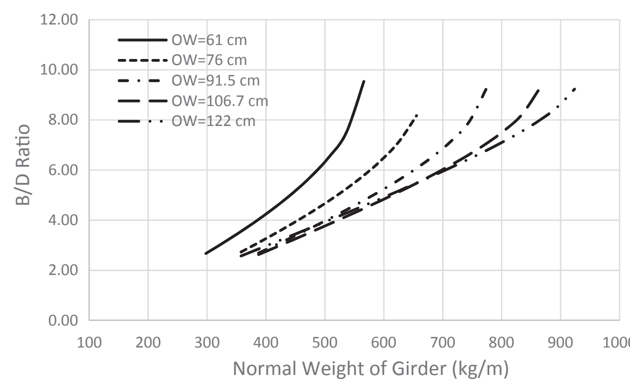
The results from the regression analysis indicated a relationship between the rotation value and the three predictors. This also implied that once the required rotation value, normal weight of girder, and overhang width were determined, the B/D ratio can be computed based on the regression equation. Thus, a simple method to determine the maximum B/D ratio was developed. This method consisted of several graphs, with each one representing a different allowable rotation value. Inside each graph, several curves related to the overhang width were included. From this analysis, the B/D ratio can be determined easily without finite element analysis or complex computation.

Figs. 10–12 show the graphs used to determine the B/D ratio based on the overhang width and normal weight of girder, with each graph representing a different allowable rotation value: 0.1, 0.2, and 0.3 degrees. The blank area in the graphs, such as in the lower left and upper right corners devoid of curves, indicate that either the selected girder section cannot satisfy the required rotation value (lower left corner), or the B/D ratio exceeded the limits placed by a restricted maximum unbraced length and minimum girder depth, meaning the rotation does not exceed the rotation limit when the other design criterions are satisfied (upper right corner).

Figs. 10–12 illustrate that for a certain allowable rotation value, the maximum B/D ratio increased with an increase of the normal weight. This is because a girder section with a larger normal weight usually

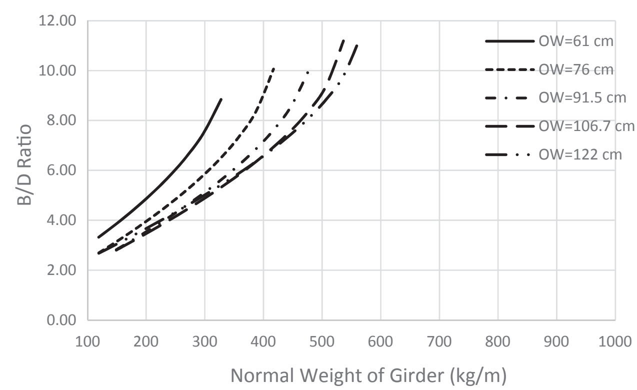
Table 5
Coefficients for the quadratic model.

Variable	Estimate coefficient
y-intercept	-3.4573
W	-2.2709×10^{-2}
OW	2.6013×10^{-1}
B/D	9.5216×10^{-1}
W × OW	1.1783×10^{-4}
W × B/D	-2.0316×10^{-3}
OH × B/D	2.3806×10^{-2}
W^2	4.6040×10^{-5}
OW^2	-9.3860×10^{-3}
B/D^2	-1.0947×10^{-1}



OW = Overhang Width

Fig. 10. B/D graph for allowable rotation value equals 0.1 degree.

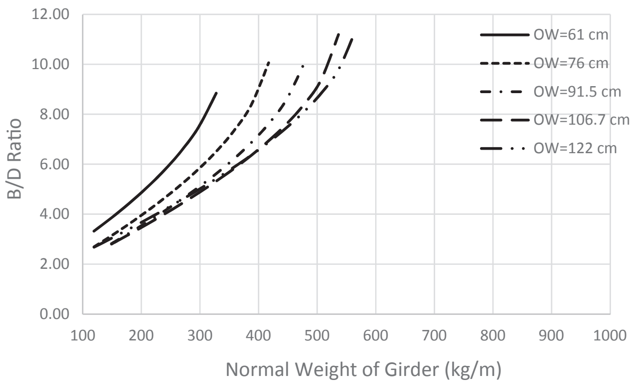


OW = Overhang Width

Fig. 11. B/D graph for allowable rotation value equals 0.2 degree.

Table 4
Three models for regression analysis.

Model	Description
Linear	$\ln(Rotation)\ 1 + OW + W + B/D$
Interaction	$\ln(Rotation)\ 1 + OW + W + B/D + OW \times W + OW \times B/D + W \times B/D$
Quadratic	$\ln(Rotation)\ 1 + OW + W + B/D + (OW + W + B/D)^2$



OW = Overhang Width

Fig. 12. B/D graph for allowable rotation value equals 0.3 degree.

shows more torsional stiffness, resulting in a lower rotation value. Also, when using a shorter overhang, a larger B/D ratio can be expected since a shorter moment arm will foster a smaller torsional moment produced from the construction loads. Moreover, with an increase of the rotation limit, a smaller unbraced length, resulting in a smaller B/D ratio, is required to resist the torsional moment.

5. Validation

The method proposed in this study to limit exterior girder rotation was validated using the experimental and finite element analysis results from the previous research [3]. Two bridges, the Bloomington Bridge and the Greenup Bridge, located in Bloomington and Greenup county (Illinois, USA), were selected for the validation of this simple method. The Bloomington Bridge used a wide flange beam section W30 × 124 for the girders, with a normal weight of 185 kg/m (124 lb/ft), and had an overhang width of 94 cm (37 in). For the Greenup Bridge, a W30 × 99 section was used and had an overhang width of 91.5 cm (36 in). The limit of rotation was 0.3 degrees for both bridges. All necessary information to determine the maximum B/D ratio is shown in Table 6. The rotation limits were determined based on the specifications in the Illinois Bridge Manual.

The temporary cross-frame and pipe-tie system are rotation prevention systems, commonly used in the United States to protect the exterior girder from excessive rotation (Fig. 13). Using the method developed in this study, the maximum B/D ratios to limit the exterior girder rotation were determined to be 3.75 and 3.30 for the Bloomington Bridge and Greenup Bridge respectively. These two systems were added to the finite element models to decrease the B/D ratio.

Fig. 14 shows the finite element analysis results for the Bloomington Bridge. When one temporary cross-frame, or pipe-tie system, was added at the middle between two diaphragms, the B/D ratio was reduced to 3.94, close to the allowable B/D ratio (3.75). The rotation dropped more than 30% and showed 5% and 28% lower than the maximum rotation value specified in IDOT Bridge Manual when using intermediate cross-frame and pipe-tie system respectively. By adding two temporary bracings between two diaphragms and reducing the B/D ratio to 2.62, the rotation values dramatically diminished to less than 70% of the maximum rotation value for both cross-frame and pipe-tie system.

Table 6
Parameters of the Bloomington bridge and Greenup bridge.

	Bloomington bridge	Greenup bridge
Girder section	W30 × 124	W30 × 99
Normal weight of girder	185 kg/m (124 lb/ft)	148 kg/m (99 lb/ft)
Overhang width	94 cm (37 in)	91.5 cm (36 in)
Rotation limit	0.3 degrees	0.3 degrees
Original B/D ratio	7.87	7.48
Maximum B/D ratio	3.75	3.30

The results of the Greenup Bridge illustrated the same trend (Fig. 15). The rotation dropped to 6% and 30% below the limit when using the temporary cross-frame and pipe-tie system separately, and the B/D ratio was reduced to 3.74, close to the allowable B/D ratio of 3.30. Adding two bracings between diaphragms resulted in a lower B/D ratio of 2.49 and lowered the rotation value to 60% and 20% of the maximum rotation value for the cross-frame and pipe-tie system respectively. The pipe-tie system showed a better performance due to the larger effective depth, which provided more torsional stiffness.

The results also demonstrated that by applying the proposed simple method, the B/D ratio can be easily determined, and the rotation can be limited to the allowable range. This method uses conservative evaluation in determining the B/D ratio for limiting the exterior girder rotation, allowing the method to be compatible with different types of lateral bracing systems.

6. Conclusion

In this research, a total of 4285 finite element models, for generating artificial data, were developed using the automatic modeling program. The stepwise variable selection method was applied to evaluate the significances of ten parameters derived from bridge geometries. The normal weight of the girder, overhang width and B/D ratio were determined to be the most significant parameters that affected the exterior girder rotation. Then, three different regression models were prepared and compared with each other; the quadratic regression model, which had a value of R^2 equaled to 0.97, was selected for developing a simple method to determine B/D ratio. The simple method had been validated using previous research results and was demonstrated to be effective. Also, this method is compatible for different type of bracing systems due to its conservative approach. The results of this research can provide bridge engineers, as well as researchers, better insight into the relationship between the exterior girder rotation and bridge geometries. Also, the method developed in this study allows bridge engineers to limit the exterior girder rotation more effectively and efficiently. The following conclusion can be drawn based on the findings of this study.

(a) The B/D ratio is an effective indicator to predict the exterior girder rotation. Also, by using the B/D ratio, two geometric parameters, the unbraced length and girder depth, can be eliminated.
(b) The normal weight of girder, overhang width and B/D ratio are the most significant parameters that affect the exterior girder rotation. The rotation value can be accurately predicted by using only these three predictors.
(c) The diaphragm depth and unbraced length also have impacts on the rotation of the exterior rotation. However, the effect of the unbraced length can be neglected when the B/D ratio is introduced into the regression model. The diaphragm depth was also neglected due to the conservative consideration of the predicting model, meaning only the worst case was considered.
(d) The B/D ratio, or the unbraced length when the depth of the girder section is determined, can be easily determined based on the rotation limit value, overhang width, and normal weight of girder.
(e) The simple method for limiting the exterior girder rotation was proven to be effective. The maximum allowable B/D ratio can be easily determined using this method without finite element analysis or complex computation. It can also be used for other types of bracing systems due the conservative nature of the method.

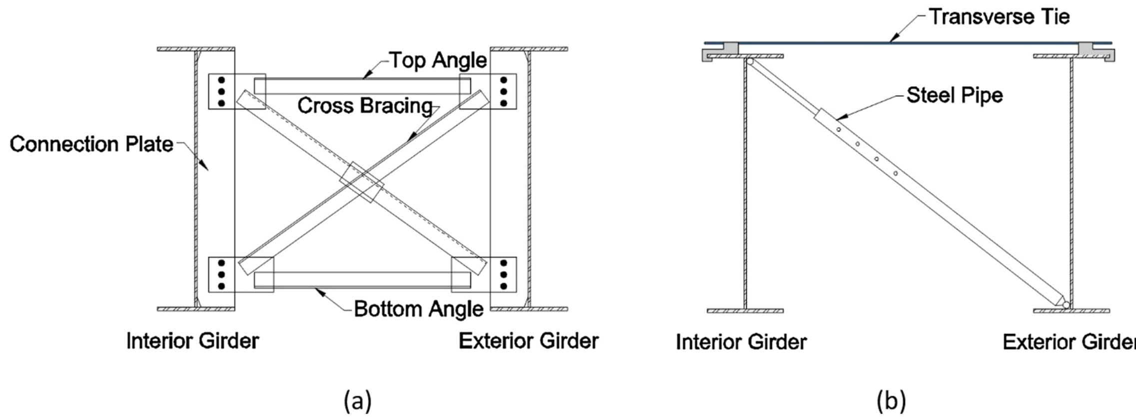


Fig. 13. Temporary rotation prevention system: (a) intermediate cross-frame (b) pipe-Tie system.

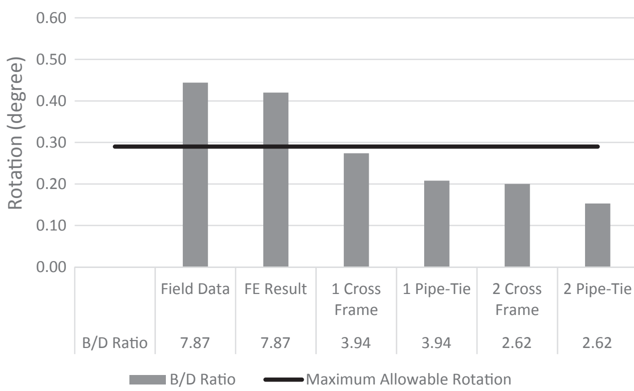


Fig. 14. B/D ratio vs rotation for Bloomington bridge.

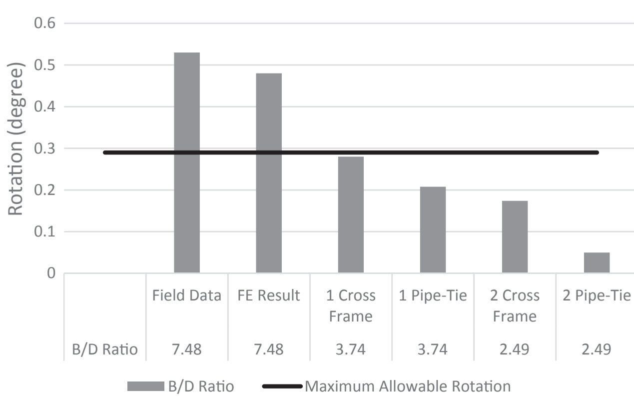


Fig. 15. B/D ratio vs rotation for Greenup bridge.

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