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Variation of Effective Slab Width for Composite Cable-Stayed Bridge

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ABSTRACT: Bridge design has developed over the centuries in a fashion that continues to improve upon the types of materials being used, as well as to use existing materials in a more efficient manner. However, with new technology such as cable stayed-bridge, the rush to implement the new concept frequently does not permit the answering of all the important engineering questions prior to implementation. A composite section is made up of a concrete slab attached to a steel girder by means of shear connectors. Under positive bending moment, part of the slab will act as the flange of the girder and will resist the longitudinal compression. When the spacing between the girders becomes large, it is evident that the simple beam theory does not strictly apply because the longitudinal compressive stress in the flange will vary with distance from girder web, the flange being more highly stressed over the web than in the extremities. This phenomenon is termed as "shear-lag". The effective width concept has been introduced, widely recognized, and implanted as a simplified practical method for design and evaluation of structural strength and stiffness while accounting for shear-lag effects indirectly. The present study aims in the evaluation of the variation of effective slab width with depth of cross girder, in cable-stayed bridge.

KEYWORDS: Composite deck; Effective width; Cable stayed bridges, SAP2000.

I. INTRODUCTION

The continuous increase of the deck spans, together with the aesthetic concerns associated with bridges, has led to cross-sections slender and stronger. The great progress in materials that has been observed in the last decades, as well as the achieved experience itself, has shown that composite steel–concrete decks are a very efficient solution. The combination of the two materials allows taking advantage of their best features, allowing the deck to be light, strong and slender. Bridge design has developed through the centuries in a fashion that continues to improve upon the types of materials being used, and also to use existing materials in a more efficient manner. Thus with new materials, construction methods, analysis methods, and design concepts are developed; they are frequently employed in bridges because of society's need for more durable, longer spans that can be built within ever-tightening public budgets. However, with new technologies like the cable-stayed bridges, the rush for implementing the concept frequently does not permit the answers of all the important questions of engineering prior to implementation. The most common composite cable-stayed deck is composed by two steel main girders, continuously suspended by cables, and a concrete slab supported on a grid formed by this main girders and cross-beams. The main girders, spaced between stay-cables, support the longitudinal and transversal bending moments while the concrete slab resists to the local loads and also mainly supports the high axial compressions introduced on the deck by the stays anchorages. Composite girders were widely used in the early 1900s. Many researchers investigated the behaviour of the composite girders both analytically and experimentally starting in the late 1930s.

In bridge engineering, a deck-girder system acting compositely is usually reduced to the analysis of a T-beam section characterized by elementary beam theory, and is called as beam-line analysis. In this approach, and consistent with beam theory, the normal longitudinal stress on the deck section is assumed to be constant. However, due to in-plane shear flexibility of the deck, the longitudinal normal stress over a centre-to-centre bridge deck section is non-uniform along its transverse cross section. The maximum value of stress occurs at the mid-line junction with the girder; and

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gradually decreases towards the centre spacing line, as shown in figure 1.1. This non-uniform distribution of stress is known as shear lag.

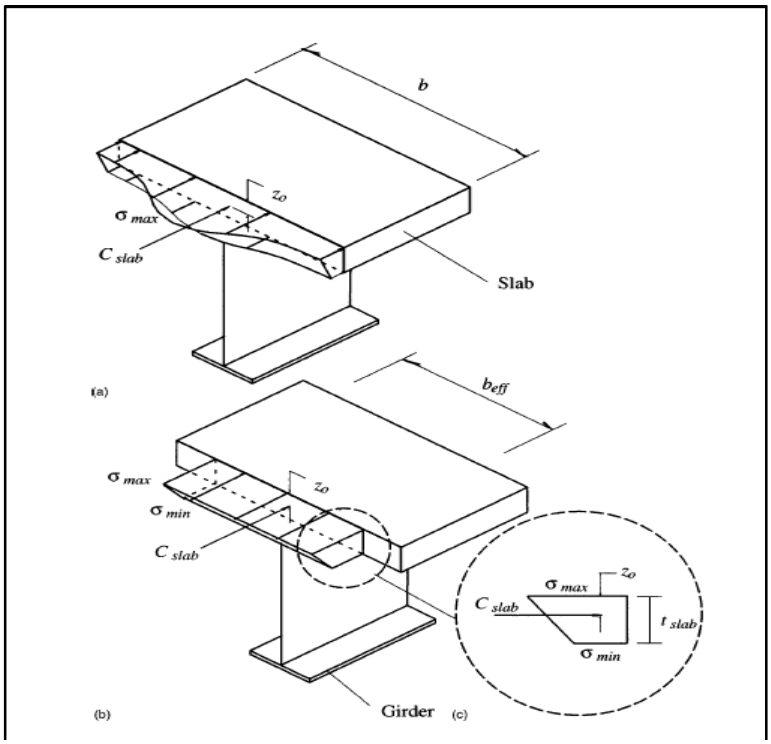

Figure 1 Effective width concepts
[Stuart S. Chen et al. (2007)]

The stress distribution depends on several factors. These factors include cross sectional dimensions and stiffness of the deck (flange) and girder and loading conditions. This results in analytical solutions not easily applicable in practice. Therefore, to simplify the problem an effective flange width is used in design practice.

II. LITERATURE REVIEW

M. Chiewanichakornet. al. (2004) in this paper, study has been carried out to evaluate and determine the actual effective slab width of steel-concrete composite bridge girders using three-dimensional non-linear finite element analysis. Based on this study a new definition for effective slab width has been proposed. Comparison with various national and international codes of practice has been carried out, to utilize a newly developed effective slab with definition from the research to verify its accuracy and conservatism. This codes include AASHTO-LRFD [AASHTO 1998], British [BSI 1979, BSI 1982], Canadian [CSA 2000, CSA 2001], Japanese [JRA 1996], and Eurocode [Eurocode 4 1992, Eurocode 4 1997] specifications.

Jonathan P. Moses et. al. (2006) this study uses results from various in situ load tests of three steel girder bridges with the same Glass Fibre-Reinforced Polymer (GFRP) deck system, to determine the degree of composite action that may be developed and the transverse distribution of wheel loads that may be assumed for these structures. The results of this study indicate that, the current design practice to treat GFRP deck systems in a manner similar to non-composite concrete decks may results in non-conservative bridge girder design. Specifically1. The effective width of the GFRP deck that may be engaged is lower than that of an equivalent concrete deck.2.The engaged effective width shows some evidence of degradation with time.3.Increased apparent moment distribution factors, indicating reduced

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transverse distribution of wheel loads, are observed due to the increased transverse distribution of wheel loads, are observed due to the increased transverse flexibility of the GFRP deck system.

Stuart S. Chen et al. (2007) this paper proposes simpler and more versatile design criteria for computing the effective width (beff) in steel-concrete composite bridges. A parametric study was conducted based on finite-element analysis of bridges selected by a statistical method – namely design of experiment concepts. Both simple-span and multiple-span continuous bridges were considered in the parametric study. The finite element methodology was validated with companion experiments on ¼ and ½ scale specimens. Effective width values at the critical sections were computed from stresses extracted from FEA models and used in developing candidate design equations. Use of full width- the most versatile, simplest and sufficiently accurate effective width design criteria, is proposed for both positive and negative moment regions.

Zhibin Lin and Jian Zhao (2011) in this paper, shear-lag effects in box girders were studied by using variation analysis method to evaluate the effective flange width provisions in the AASHTO specifications. To determine the most influential factors for shear lag behaviour in the girders, a parametric study was also conducted. The study indicated that beam-width-over-span ratio, flange thickness, the longitudinal flange stiffeners and the material properties need to be considered in determining effective flange width. Based on the study, recommendations for the effective flange width provisions of AASHTO specifications were suggested.

F. Garaet. al. (2011) this paper presents a simplified analysis method for the design of twin-girder and single box steel-concrete composite bridge decks. The main advantage of the study is its ability to determine the normal longitudinal stress distribution in the slab based on the results of a structural global analysis carried out using the real geometry of the deck, i.e. without considering the use of effective widths. New analytical expressions are presented in this paper to calculate the effective width. The approach presented in the paper is capable of handling different loading conditions, such as constant uniformly distributed loads, envelops of transverse actions due to traffic loads, support settlements and concrete shrinkage. The first part of the paper describes about the results of an extensive parametric study carried out by means of finite element formulation, based on which various analytical expressions have been obtained. Finally, a realistic case study of a bridge with varying cross-section is considered to show the robustness of proposed methodology.

Wenchao Song et. al. (2013) in this paper the equivalent strip width for stiffness-driven design of FRP superstructures is been proposed. The paper demonstrates that using a Timoshenko beam approximation 2D special orthotropic plates idealized from FRP superstructures can be designed as 1D beam. To calculate the equivalent strip width to determine deflection at points of interest in practical design, a tractable and accurate analytical solution is first derived in accordance with classical laminate plate theory (CLPT). The paper then shows that the equivalent strip width obtained from the analytical solution together with Timoshenko beam theory is sufficient to calculate both flexural deflections and the deflections due to out of plane shear deformations. The equivalent strip width calculation is further simplified, for the FRP superstructures in current practice, by considering only two or three key parameters identified by this paper. Hence, the difficulty of making excessive assumptions about both material and section properties of an FRP superstructure at the beginning of its design can be overcome by the simplified equivalent strip width. Based on the results of the paper, a new design procedure is proposed.

III. METHODOLOGY

In this study, a three-dimensional finite element analysis is employed to evaluate and determine the actual effective slab width of steel-concrete composite bridge girders, by varying the depth of cross girders.The three-dimensional models used beam finite linear elements for the steel structures of the deck, and of the towers and cables. Finite elements of the slab, plans and four-nodes, based on the theory of thin slabs to represent the concrete slab. The details of the bridge are shown in figure no. 1. In the current study effective width has been found for the dead load. Dead load refers to the gravity loads of structural members such as bridge decks, tower (i.e., pylon), piers, cables, etc. Also gravity load of non-structural elements placed on the bridge structure after concrete hardened, which include bridge railings, pavement.Necessary restraints have been assigned to certain joints from the total joints as per the boundary conditions.

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IV. ANALYTICAL RESULTS

A bridge model prepared in SAP software was analyzed for the dead load and cable forces. After analysis sections were drawn at a regular interval of 3m along the length of the bridge. These sections give the values of total axial force and,stress values at the section. By using the definition given in following equation, values of effective width and effective

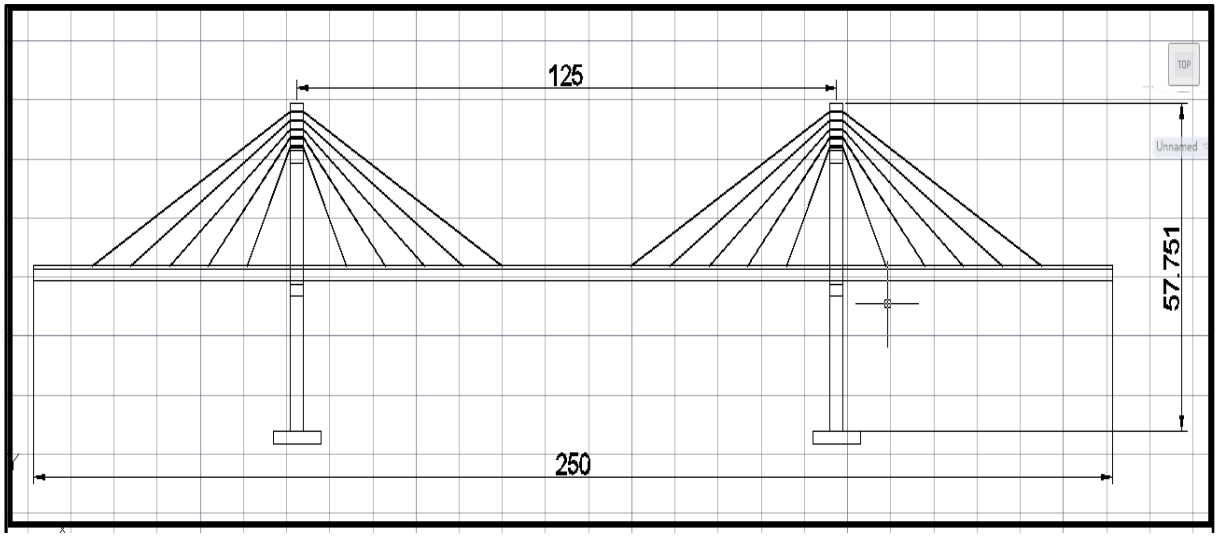

Figure No.2 Bridge details

Width factor at every section is calculated. $b_{eff} = \frac{1}{\sigma max} \int_{-b/2}^{b/2} \sigma \, dy$ (equation 1)Where b_{eff} is effective slab width and b is physical slab width. [Amjad J. Aref (2007)]. Table No. 1 shows the values of total axial force, stress, effective width and effective width factor for the.

Table No. 1.Effective width for the model having depth of main girder 1.5 m and depth of cross girder 1.0 m.

Section (m)	Force (kN)	Max stress (kN/m^2)	Min stress (kN/m^2)	Avg. stress (kN/m^2)	B_{eff} (m)	*Beff* factor
12	2065.00	4800	2400	3600	1.9120	0.1593
15	2849.60	4800	2400	3600	2.6385	0.2199
18	4130.00	4800	2400	3600	3.8241	0.3187
21	3501.62	4800	2400	3600	3.2422	0.2702
24	4437.78	4800	2400	3600	4.1091	0.3424
27	6486.00	2400	2400	2400	9.0083	0.7507
30	6486.00	2400	2400	2400	9.0083	0.7507
33	8786.00	2400	2400	2400	12.2028	1.0169
36	8786.00	2400	2400	2400	12.2028	1.0169
39	8786.00	4800	2400	3600	8.1352	0.6779
42	10140.00	7200	4800	6000	5.6333	0.4694

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45	10140.00	7200	4800	6000	5.6333	0.4694
48	10140.00	12000	9600	10800	3.1296	0.2608
51	11854.00	12000	9600	10800	3.6586	0.3049
54	11854.00	14400	12000	13200	2.9934	0.2495
57	11854.00	16800	14400	15600	2.5329	0.2111
60	11854.00	21600	19200	20400	1.9369	0.1614
63	6496.95	28800	26400	27600	0.7847	0.0654
66	6496.95	19200	16800	18000	1.2031	0.1003
69	6496.95	16800	14400	15600	1.3882	0.1157
72	6496.95	9600	7200	8400	2.5782	0.2148
75	6496.95	9600	7200	8400	2.5782	0.2148
78	6496.95	9600	7200	8400	2.5782	0.2148
81	3384.95	4800	2400	3600	3.1342	0.2612
84	3384.95	2400	2400	2400	4.7013	0.3918
87	3384.95	2400	2400	2400	4.7013	0.3918
90	2048.95	7200	4800	6000	1.1383	0.0949
93	2048.95	9600	7200	8400	0.8131	0.0678
96	2048.95	9600	7200	8400	0.8131	0.0678
99	425.04	12000	9600	10800	0.1312	0.0109
102	425.04	14400	12000	13200	0.1073	0.0089
105	425.04	14400	12000	13200	0.1073	0.0089
108	1571.04	14400	12000	13200	0.3967	0.0331
111	1571.04	16800	14400	15600	0.3357	0.0280
114	8561.05	14400	12000	13200	2.1619	0.1802
117	8561.05	16800	14400	15600	1.8293	0.1524
120	8561.05	19200	16800	18000	1.5854	0.1321
123	8561.05	19200	16800	18000	1.5854	0.1321
126	8561.05	19200	16800	18000	1.5854	0.1321
129	8561.05	19200	16800	18000	1.5854	0.1321
132	8561.05	19200	16800	18000	1.5854	0.1321
135	8561.05	16800	14400	15600	1.8293	0.1524
138	8561.05	14400	12000	13200	2.1619	0.1802
141	1571.04	16800	14400	15600	0.3357	0.0280
144	1571.04	16800	14400	15600	0.3357	0.0280
147	427.04	14400	12000	13200	0.1078	0.0090
150	427.04	14400	12000	13200	0.1078	0.0090
153	427.04	12000	9600	10800	0.1318	0.0110
156	366.84	9600	7200	8400	0.1456	0.0121
159	2048.95	9600	7200	8400	0.8131	0.0678
162	2048.95	7200	4800	6000	1.1383	0.0949
165	2048.95	4800	2400	3600	1.8972	0.1581
168	3386.95	2400	2400	2400	4.7041	0.3920
171	3386.95	4800	2400	3600	3.1361	0.2613
174	3386.95	9600	7200	8400	1.3440	0.1120
177	5100.95	9600	7200	8400	2.0242	0.1687
180	5100.95	12000	9600	10800	1.5744	0.1312
183	5100.95	19200	16800	18000	0.9446	0.0787
186	5100.95	19200	16800	18000	0.9446	0.0787
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228	6488.00	4800	2400	3600	6.0074	0.5006
231	6488.00	4800	2400	3600	6.0074	0.5006
234	4130.00	4800	2400	3600	3.8241	0.3187
237	4130.00	4800	2400	3600	3.8241	0.3187
240	4130.00	4800	2400	3600	3.8241	0.3187

Table 2.Effective width for the model having depth of main girder 1.5 m and depth of cross girder 1.5 m.

Section (m)	Force (kN)	Max stress (kN/m^2)	Min stress (kN/m^2)	Avg. stress (kN/m^2)	B_{eff} (m)	*Beff* factor
12	2065.00	5500	5500	5500	1.2515	0.1043
15	2849.23	5500	5500	5500	1.7268	0.1439
18	4130.00	5500	5500	5500	2.5030	0.2086
21	3500.87	5500	5500	5500	2.1217	0.1768
24	4437.54	5500	5500	5500	2.6894	0.2241
27	6486.00	5500	5500	5500	3.9309	0.3276
30	6486.00	5500	5500	5500	3.9309	0.3276
33	8786.00	5500	5500	5500	5.3248	0.4437
36	8786.00	5500	5500	5500	5.3248	0.4437
39	8786.00	5500	5500	5500	5.3248	0.4437
42	10140.00	5500	5500	5500	6.1455	0.5121
45	10140.00	5500	5500	5500	6.1455	0.5121
48	10140.00	11000	5500	8250	4.0970	0.3414
51	11854.00	16500	11000	13750	2.8737	0.2395
54	11854.00	16500	11000	13750	2.8737	0.2395
57	11854.00	16500	11000	13750	2.8737	0.2395
60	11854.00	22000	16500	19250	2.0526	0.1711
63	6496.66	22000	16500	19250	1.1250	0.0937
66	6496.66	22000	16500	19250	1.1250	0.0937
69	6496.66	16500	11000	13750	1.5749	0.1312
72	6496.66	16500	11000	13750	1.5749	0.1312
75	6496.66	11000	5500	8250	2.6249	0.2187
78	6496.66	11000	5500	8250	2.6249	0.2187
81	3384.66	5500	5500	5500	2.0513	0.1709
84	3384.66	5500	5500	5500	2.0513	0.1709
87	3384.66	5500	5500	5500	2.0513	0.1709
90	2048.66	11000	5500	8250	0.8277	0.0690
93	2048.66	11000	5500	8250	0.8277	0.0690
96	2048.66	11000	5500	8250	0.8277	0.0690
99	425.33	16500	11000	13750	0.1031	0.0086
102	425.33	16500	11000	13750	0.1031	0.0086
105	425.33	16500	11000	13750	0.1031	0.0086

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141	1571.33	22000	16500	19250	0.2721	0.0227
144	1571.33	22000	16500	19250	0.2721	0.0227
147	427.33	16500	11000	13750	0.1036	0.0086
150	427.33	16500	11000	13750	0.1036	0.0086
153	427.33	16500	11000	13750	0.1036	0.0086
156	427.33	11000	5500	8250	0.1727	0.0144
159	2048.66	11000	5500	8250	0.8277	0.0690
162	2048.66	11000	5500	8250	0.8277	0.0690
165	2048.66	5500	5500	5500	1.2416	0.1035
168	3386.66	5500	5500	5500	2.0525	0.1710
171	3386.66	11000	5500	8250	1.3683	0.1140
174	3386.66	11000	5500	8250	1.3683	0.1140
177	5100.66	11000	5500	8250	2.0609	0.1717
180	5100.66	16500	11000	13750	1.2365	0.1030
183	5100.66	16500	11000	13750	1.2365	0.1030
186	5100.66	22000	16500	19250	0.8832	0.0736
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201	11856.00	16500	11000	13750	2.8742	0.2395
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222	8788.00	5500	5500	5500	5.3261	0.4438
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231	6488.00	5500	5500	5500	3.9321	0.3277
234	4130.00	5500	5500	5500	2.5030	0.2086
237	4130.00	5500	5500	5500	2.5030	0.2086
240	4130.00	5500	5500	5500	2.5030	0.2086

Table 3 Effective width for the model having depth of main girder 1.5 m and depth of cross girder 2.0 m.

Section (m)	Force (kN)	Max stress (kN/m^2)	Min stress (kN/m^2)	Avg. stress (kN/m^2)	B_{eff} (m)	*Beff* factor
12	2065.00	2500	2500	2500	2.7533	0.2294
15	2848.88	5000	2500	3750	2.5323	0.2110
18	4130.00	5000	2500	3750	3.6711	0.3059
21	3500.00	2500	2500	2500	4.6667	0.3889
24	4437.32	5000	2500	3750	3.9443	0.3287
27	6486.00	2500	2500	2500	8.6480	0.7207
30	6486.00	2500	2500	2500	8.6480	0.7207
33	8786.00	2500	2500	2500	11.7147	0.9762

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51	11857.00	10000	7500	8750	4.5170	0.3764
54	11854.00	12500	10000	11250	3.5123	0.2927
57	11854.00	15000	12500	13750	2.8737	0.2395
60	11854.00	20000	17500	18750	2.1074	0.1756
63	6496.39	30000	27500	28750	0.7532	0.0628
66	6496.39	20000	17500	18750	1.1549	0.0962
69	6496.39	15000	12500	13750	1.5749	0.1312
72	6496.39	10000	7500	8750	2.4748	0.2062
75	6496.39	7500	5000	6250	3.4647	0.2887
78	6496.39	10000	7500	8750	2.4748	0.2062
81	3384.39	5000	2500	3750	3.0084	0.2507
84	3384.39	2500	2500	2500	4.5125	0.3760
87	3384.39	5000	2500	3750	3.0084	0.2507
90	2048.39	7500	5000	6250	1.0925	0.0910
93	2048.39	7500	5000	6250	1.0925	0.0910
96	2048.39	10000	7500	8750	0.7803	0.0650
99	425.61	12500	10000	11250	0.1261	0.0105
102	425.61	15000	12500	13750	0.1032	0.0086
105	425.61	17500	15000	16250	0.0873	0.0073
108	1571.61	20000	17500	18750	0.2794	0.0233
111	1571.61	20000	17500	18750	0.2794	0.0233
114	8561.61	15000	12500	13750	2.0755	0.1730
117	8561.61	17500	15000	16250	1.7562	0.1464
120	8591.61	20000	17500	18750	1.5274	0.1273
123	8561.61	20000	17500	18750	1.5221	0.1268
126	8561.61	20000	17500	18750	1.5221	0.1268
129	8561.61	20000	17500	18750	1.5221	0.1268
132	8561.61	20000	17500	18750	1.5221	0.1268
135	8561.61	17500	15000	16250	1.7562	0.1464
138	8561.61	15000	12500	13750	2.0755	0.1730
141	1571.61	17500	15000	16250	0.3224	0.0269
144	1571.61	17500	15000	16250	0.3224	0.0269
147	427.61	12500	10000	11250	0.1267	0.0106
150	427.61	12500	10000	11250	0.1267	0.0106
153	427.61	10000	7500	8750	0.1629	0.0136
156	427.61	7500	5000	6250	0.2281	0.0190
159	2048.39	7500	5000	6250	1.0925	0.0910
162	2048.39	7500	5000	6250	1.0925	0.0910
165	2048.39	5000	2500	3750	1.8208	0.1517
168	3386.39	2500	2500	2500	4.5152	0.3763
171	3386.39	5000	2500	3750	3.0101	0.2508
174	3386.39	7500	5000	6250	1.8061	0.1505
177	5100.39	10000	7500	8750	1.9430	0.1619
180	5100.39	12500	10000	11250	1.5112	0.1259
183	5100.39	17500	15000	16250	1.0462	0.0872
186	5100.39	20000	17500	18750	0.9067	0.0756
189	11856.00	30000	27500	28750	1.3746	0.1146
192	11856.00	20000	17500	18750	2.1077	0.1756
195	11856.00	17500	15000	16250	2.4320	0.2027
198	11856.00	15000	12500	13750	2.8742	0.2395
201	11856.00	12500	10000	11250	3.5129	0.2927
204	11856.00	10000	7500	8750	4.5166	0.3764
207	10142.00	7500	5000	6250	5.4091	0.4508
210	10142.00	5000	2500	3750	9.0151	0.7513
213	10142.00	5000	2500	3750	9.0151	0.7513

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216	8788.00	2500	2500	2500	11.7173	0.9764
219	8788.00	2500	2500	2500	11.7173	0.9764
222	8788.00	2500	2500	2500	11.7173	0.9764
225	6488.00	2500	2500	2500	8.6507	0.7209
228	6488.00	5000	2500	3750	5.7671	0.4806
231	6488.00	2500	2500	2500	8.6507	0.7209
234	4130.00	5000	2500	3750	3.6711	0.3059
237	4130.00	5000	2500	3750	3.6711	0.3059
240	4130.00	2500	2500	2500	5.5067	0.4589

The variation effective width and *Beff* Parameter along the length of the deck is shown in the following graph.

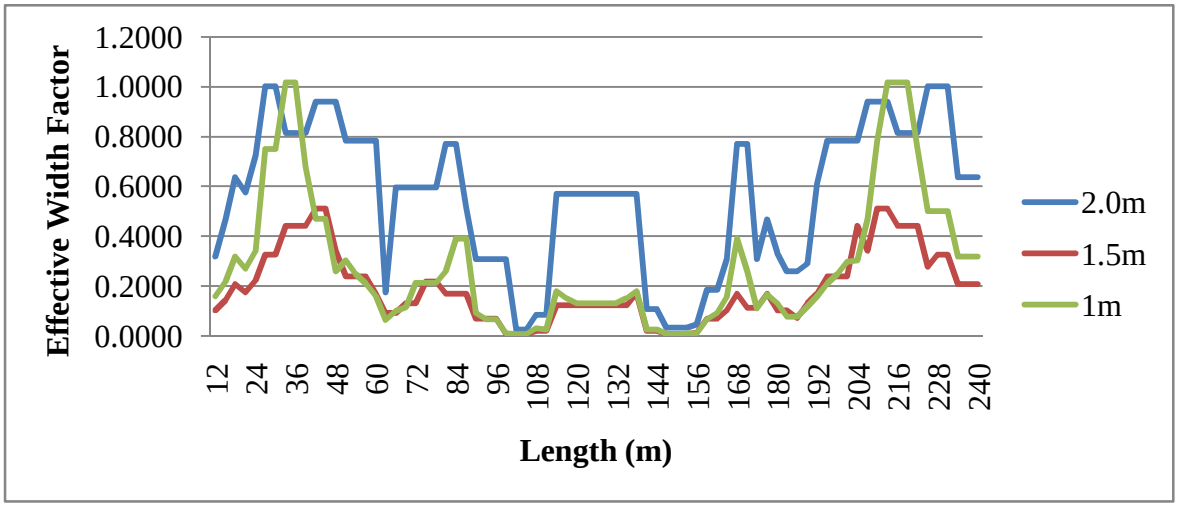

Figure No. 4 Comparison of effective width factor for different sizes of cross girder

V. CONCLUSION

The analytical study was carried out to determine the effective slab width value for composite steel-concrete cable stayed bridge. The analysis results lead to the following conclusions. The effective width values change throughout the length of the bridge. The main reason behind the change in the effective width values is the variation of axial force. The variation in axial force is due to variation of cable forces in the deck. The effective slab width at the initial sections as well as sections towards is negligible due to the absence of axial force.

The values in the last column are ratios of observed effective width to the available width, i.e. effective width parameter. The range of this parameter is from 0.47 to 1. The same range of values is obtained in the present study.

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