ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 8, NO. 4 (2007)
PAGES 423-442

SERVICE LOAD BEHAVIOR OF CONTINUOUS COMPOSITE BEAMS WITH PRECAST DECKS CONSIDERING CREEP, SHRINKAGE AND CRACKING

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ABSTRACT

Systematic studies are reported for the service load behavior of continuous beams with precast decks. A hybrid procedure recently developed by the authors has been used for carrying out the studies. The procedure accounts for creep, shrinkage and progressive cracking of concrete of the decks. The age of concrete at the time of loading, magnitude of load, grade of concrete, relative humidity and tension stiffening are the parameters whose effects have been studied on the bending moments at the supports and midspan deflections. The relative humidity is found to be the more significant parameter affecting the time-dependent changes, in bending moments at supports and midspan deflections.

Keywords: Composite beam, cracking, creep, shrinkage, service load, deflection

1. INTRODUCTION

The steel-concrete composite beam is one of the economical forms of construction, Figure 1. Combination of steel and concrete systems has been conceived on the premises that each type of construction offers a natural advantage which when utilized together results in an efficient system. Further, the composite beams with precast decks have an advantage in the speed of construction. In continuous composite beams subjected to service load, in addition to instantaneous cracking, the time-dependent effects of creep and shrinkage in concrete can lead to the progressive cracking of concrete deck near interior supports and result in considerable moment redistribution along with increase in deflections.

Extensive literature is available on the instantaneous and time-dependent behavior of the continuous composite beams. Dezi and Tarantino [1] carried out parametric studies on two span continuous composite beams. The effect of three rheological parameters i.e. compressive strength of concrete (f_{ck}), relative humidity (RH) and age of concrete at loading

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(t_1) was studied on the time-dependent behavior. The concrete was assumed to be uncracked and further the effect of shrinkage was not considered in these studies. Virtuoso and Vieira [2] have studied the time-dependent behavior of two span continuous composite beams with flexible connection and concluded that the effect of creep simultaneously with shrinkage is more important than the effect of creep alone. The individual effect of various rheological factors has not been studied. Ranzi [3] has presented the studies on the behavior of simply supported composite beams stiffened by longitudinal plates, thereby, neglecting the cracking. The effect of relative humidity and compressive strength has been studied and relative humidity has been found to be the major factor influencing the time-dependent behavior. Some other studies [4,5] have also been reported for the time-dependent behavior of continuous composite beams. These studies are mainly related to the effect of construction sequence and in these, the overall effect of creep and shrinkage but not of the individual rheological parameters is presented. Studies are also available on the time-dependent effects of precast prestressed concrete girder bridges [6,7], in which, the relative effect of creep and shrinkage [6] and of some rheological factors [7] has been presented.

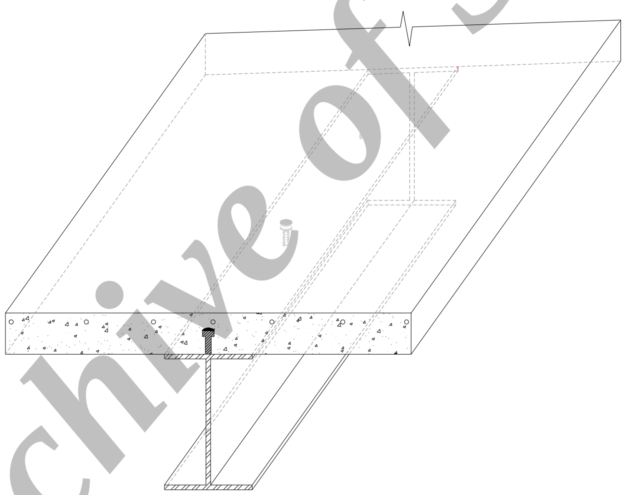


Figure 1. Isometric view of a composite beam

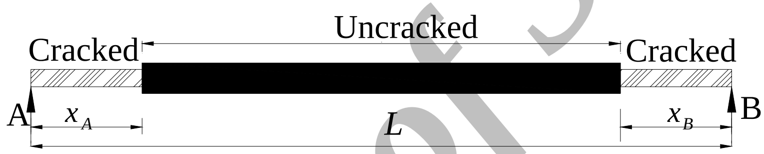
In the regions, where the tensile stress exceeds the tensile strength of the concrete, cracking occurs. The length of the cracked portion, along with the other factors, depends on the magnitude of load, w. Owing to the distributed nature of cracking, the effective rigidity of the sections is higher than the rigidity of the cracked sections (tension stiffening effect). The displacements may be overestimated if this effect is neglected [8].

In none of the above studies, the effect of all the individual parameters i.e t_1, w, f_{ck}, RH and tension stiffening is reported, nor do the studies relate specifically to the composite beams with precast decks. The present paper therefore reports systematic studies for the service load behavior of composite beams with precast decks. The parameters whose effects have been studied on the bending moments at the supports and midspan deflections are

t_1, w, f_{ck}, RH and tension stiffening.

2. HYBRID PROCEDURE FOR ANALYSIS OF CONTINUOUS COMPOSITE BEAMS

As stated earlier, the recently developed hybrid analytical-numerical procedure [9] for the composite frames and beams has been used for analyzing the continuous composite beams. The procedure is highly computationally efficient and takes into account the non-linear effects of concrete cracking and time-dependent effects of creep and shrinkage in concrete portion of the composite beams. The procedure is analytical at the elemental level and numerical at the structural level. A cracked span length beam element consisting of an uncracked zone in the middle and cracked zones at the ends has been used in the procedure, Figure 2a.



(a) Zones

(b) Releases 1 and 2

Figure 2. Cracked span length beam element

The analysis in the hybrid procedure is carried out in two parts. In the first part, instantaneous analysis is carried out using an iterative method. In the second part, time-dependent analysis is carried out by dividing the time into a number of time intervals to take into account the progressive nature of cracking of concrete Figure 3. In the time-dependent analysis, crack length is assumed to be constant and equal to that at the beginning of the time-interval, as shown in Figure 3. The age-adjusted effective modulus method [10] is used for predicting the creep and shrinkage effects.

Closed form expressions for flexibility coefficients, end displacements, crack lengths and midspan deflection of the cracked span length beam element have been used in order to reduce the computational effort. The closed form expressions for the flexibility coefficients f_{11}, f_{12}, f_{21} and f_{22} (w.r.t. releases 1 & 2) of the typical span length beam element (Figure 2b) are given as [9]

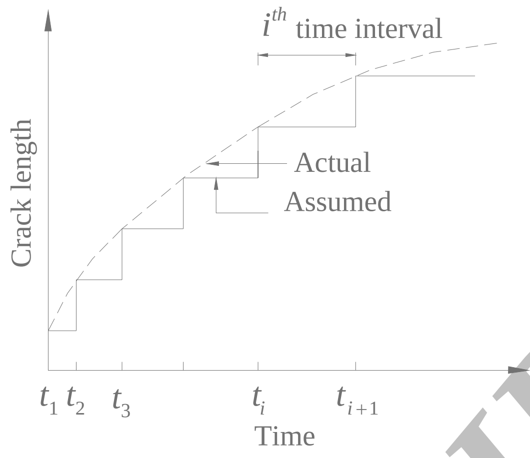


Figure 3. Actual and assumed progressive nature of cracking

$$f_{11} = \frac{1}{3L^2}\left[S_{un}^x\left(\eta_A L^3 - \xi_B x_B{}^3 + \xi_A y_A{}^3\right) + S_{cr}^x\left(\xi_A L^3 + \xi_B x_B{}^3 - \xi_A y_A{}^3\right)\right] \quad (1)$$

$$f_{12} = f_{21} = \frac{1}{6L^2}\left[\xi_A x_A{}^2\left(2x_A - 3L\right) + \xi_B x_B{}^2\left(2x_B - 3L\right)\right]\left(S_{cr}^x - S_{un}^x\right) - \frac{S_{un}^x L}{6} \quad (2)$$

$$f_{22} = \frac{1}{3L^2}\left[S_{un}^x\left(\eta_B L^3 - \xi_A x_A{}^3 + \xi_B y_B{}^3\right) + S_{cr}^x\left(\xi_B L^3 + \xi_A x_A{}^3 - \xi_B y_B{}^3\right)\right] \quad (3)$$

where, ξ_A and ξ_B = interpolation coefficients for the cracked zones at ends A and B respectively to account for the tension stiffening effect; $\eta_A = 1 - \xi_A$; $\eta_B = 1 - \xi_B$; x_A and x_B =crack lengths at ends A and B respectively; $y_A = L - x_A$; $y_B = L - x_B$; and S^x is given as

$$S^x = \frac{A}{E_c\left(AI - B^2\right)} \quad (4)$$

where E_c = modulus of elasticity of concrete; A = area of the transformed cross-section and B, I = first and second moment of area of the transformed cross-section about the reference axis respectively. The quantity S_{un}^x is evaluated using the uncracked state properties whereas S_{cr}^x is evaluated using the cracked state properties.

Similarly, the closed form expressions for other quantities may be obtained from Chaudhary et al. [9] on putting the terms corresponding to axial force as zero.

This hybrid procedure [9] has been validated by comparing the results with the experimental and analytical results for two span continuous composite beams. Further, the procedure has also been validated with the FEM model for a composite frame using ABAQUS.

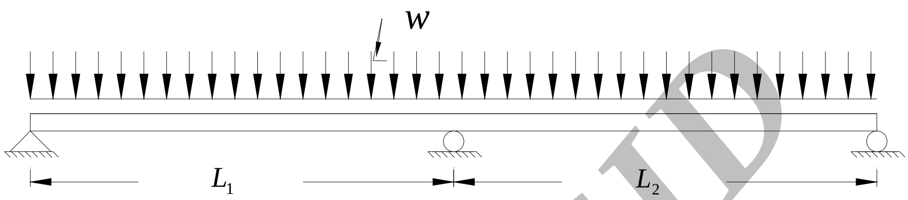
3. BEHAVIORAL STUDY

CEB-FIP MC90 [11] along with its update, *fib* [12] is used for predicting the properties of the concrete as well as the creep coefficients and shrinkage strains. The updated model is referred to as CEB-FIP MC90-99 in the paper. Cement is assumed to be of normal type and mean temperature is assumed to be 20 degree Celsius. Unless stated otherwise, a total time-duration of 20,000 days is considered and is divided into 20 time intervals. At the time of application of the load, instantaneous bending moments, $M^{it}(t_1)$ (in which, here and subsequently for other quantities having one term in the parentheses, the term indicates the time instant at which the quantity is evaluated or assumed to arise), and instantaneous midspan deflections, $d_m^{it}(t_1)$ are obtained neglecting cracking (elastic values) and considering cracking (inelastic values). It may be noted that the inelastic values, here and later on, refer to the non linearity introduced by cracking of concrete only and does not refer to any other nonlinearity. For the time-dependent analysis (t_1, t_2, ..., t_{21}), total bending moments, $M^t(t)$ and total midspan deflections, $d_m^t(t)$ at time t are obtained by considering the cracked state at t_1 and subsequent progressive cracking.

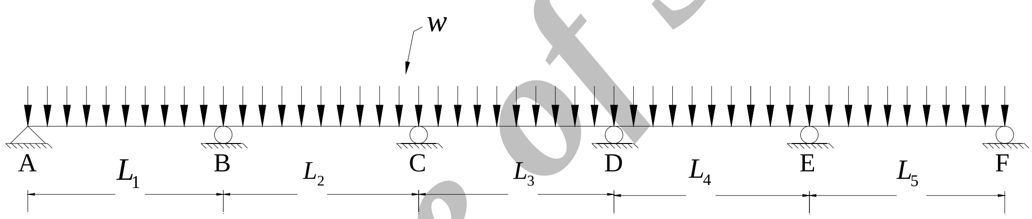
Studies, are first reported for the four parameters $(t_1,\ w,\ f_{ck}$ and RH$)$ by varying each of the parameters in turn and keeping other three parameters constant. Tension stiffening is included in these studies. Then, the effect of tension stiffening is studied by keeping the other parameters constant. It may be noted that, for concrete specimens, the compressive strength of concrete (grade of concrete) and the relative humidity have been identified as the two most important parameters affecting creep and shrinkage, by Howells et al. [13].

3.1 Effect of concrete age at time of loading/formation of composite section

First, the results have been obtained for two cast in situ two-span continuous composite beams EB1, EB2 of length $L_1 = L_2 = 5.8\,\text{m}$ (Figure 4(a)) for which the experimental results were reported by Gilbert and Bradford [14] for 340 days (creep coefficient, ϕ=1.68; shrinkage strain, ε^{sh}=0.00052). The cross-section of the composite beams consisted of a steel section (203×113UB 25) and a concrete slab of dimension 1000 mm×70 mm with a reinforcement of area 213 mm^2 placed at a distance of 15 mm from the top fiber. The properties of concrete at 28 days were: modulus of elasticity of concrete, E_c=22000 N/mm^2; tensile strength, f_{ct}=3.0 N/mm^2 and modulus of elasticity of steel, E_s=2×10^{5}N/mm^2. The beam EB1 was subjected to w=6.67 kN/m whereas beam EB2 was subjected to w=1.92 kN/m. Since in this case, the creep coefficient and shrinkage strains are already reported, only their variation with time is assumed to vary in accordance with CEB-FIP MC 90-99. The construction is assumed to be of propped type and beams are assumed to be loaded as soon as props are removed. The load is thus resisted by the composite section. It may be noted that in the continuous composite beams with the cast in situ concrete and propped construction, the effect of shrinkage, up to the time the props are present, would be negligible if the props are at a sufficiently close spacing. Therefore, such beams would behave in a manner similar to composite beams with precast decks. The concrete age at time of loading (age at loading) of the beams has not been specified by Gilbert and Bradford [14], therefore two ages at loading i.e t_1 =3 days and 7 days are considered. Further, the same values of ϕ (=1.68) and ε^{sh} (=0.00052) have been assumed for both the ages of loading.



(a) EB1, EB2



(b) EB3

Figure 4. Longitudinal profile of beams

Figure 5 presents the midspan deflections of the beams, $d_m^t(t)$, obtained by the hybrid procedure for t_1 =3 days and 7 days along with the results of the experimental study. It may be noted that the effect of age at loading (t_1) is small on the total midspan deflections. This owes to the fact that the same values of ϕ (=1.68) and ε^{sh} (=0.00052) as reported in the experimental study have been assumed for both the ages of loading. The small effect may be attributed to different magnitudes of instantaneous crack lengths owing to different tensile strengths at the time of application of load.

Now consider continuous composite beams with precast decks. The construction is assumed to be propped with the props assumed to be removed, on the formation of the composite section. It is also assumed that the load gets applied at the same time and is resisted by the composite section.

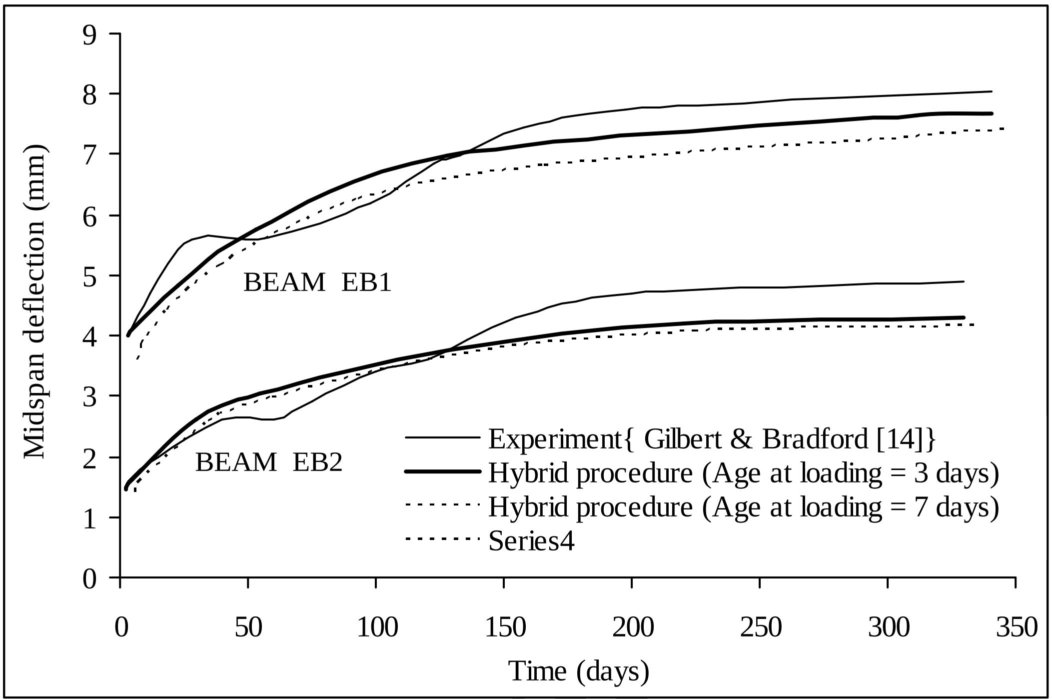


Figure 5. Midspan deflections of beams EB1 and EB2

Consider a five span beam of equal spans designated as example beam EB3 [Figure 4(b), L_1=L_2=L_3=L_4=L_5=7.0m]. The cross-section is assumed to consist of a steel section (254×146UB 43) and a concrete slab of dimension 1000mm×75 mm with a reinforcement of area 113 mm^2 placed at a distance of 15 mm from the top fiber.

Three values of t_1 (=7 days, 14 days and 21 days) are considered. The concrete is assumed to be cured for 7 days in all three cases i.e. $t_s = 7$ days. The other data chosen is: $w = 9.00$ kN/m; $f_{ck} = 30\,\mathrm{N/mm^2}$ and RH = 70%. Unless stated otherwise, the load w includes self-weight, superimposed dead load and the portion of live load which is permanent in nature. For $t_1 = 7$ days, 14 days and 21 days, the values of creep coefficient ϕ at time t_{21} for age of loading t_1 i.e. $\phi(t_{21}, t_1)$ are obtained as 2.50, 2.36 and 2.26 respectively and the values of shrinkage strain ε^{sh} for the time duration t_1 to t_{21} i.e. $\varepsilon^{sh}(t_{21}, t_1)$ are obtained as 436.7×10^{-6}, 355.3×10^{-6} and 323.5×10^{-6} respectively. It may be noted that there is pronounced effect of t_1 on the shrinkage strain $\varepsilon^{sh}(t_{21}, t_1)$.

The effect of t_1 on instantaneous inelastic (considering cracking) bending moment $M^{it}(t_1)$ and total bending moment $M^{t}(t_{21})$, at supports B and C only (noting the symmetry of the beam), is shown in Table 1. It is seen that, as expected, changes due to cracking, in elastic $M^{it}(t_1)$ are smaller for higher age of loading. This owes to less cracking due to high tensile strength at greater age of loading. It is also observed from Table 1 that there is a significant effect of t_1 on the changes, due to creep and shrinkage, in inelastic $M^{it}(t_1)$; these changes for $t_1 = 7$ days, 14 days and 21 days being about 81%, 65% and 59% respectively at support B and 79%, 64% and 53% respectively at support C. The significant effect owes to the pronounced effect of t_1 on the shrinkage strain $\varepsilon^{sh}(t_{21}, t_1)$ (as stated earlier). As expected, there is reduction in $M^t(t_{21})$ with increase in t_1.

Table 1. Effect of t_1 on instantaneous and total bending moments at supports of beam EB3 for $w = 9.00$ kN/m, $f_{ck} = 30$ N/mm^2 and RH=70%

Support	t_1 **(Days)**	**Bending Moment (kN m)** Instantaneous, $M^{it}(t_1)$: **Elastic (No cracking)**	**Bending Moment (kN m)** Instantaneous, $M^{it}(t_1)$: **Inelastic (Cracking)**	**Bending Moment (kN m)** **Total,** $M^t(t_{21})$ **(Including creep and shrinkage)**	**Time-dependent % change***
(1)	(2)	(3)	(4)	(5)	(6)
B	7	46.42	44.40	80.18	80.59
	14	46.42	45.39	74.87	64.95
	21	46.42	45.79	72.72	58.81
C	7	34.82	35.17	63.00	79.13
	14	34.82	35.01	57.44	64.06
	21	34.82	34.94	55.30	52.55

*$100\times$ [column (5)-column (4)]/column (4)

The effect of t_1, on elastic $d_m^{it}(t_1)$, inelastic $d_m^{it}(t_1)$ and $d_m^{t}(t_{21})$ for spans AB, BC and CD is shown in Table 2. Again, as for elastic $M^{it}(t_1)$, change due to cracking in elastic $d_m^{it}(t_1)$ is smaller for higher t_1. Also, there is a some effect of t_1 on the changes, due to creep and shrinkage, in inelastic $d_m^{it}(t_1)$; these changes for $t_1 = 7$ days, 14 days and 21 days being about 108%, 92% and 85% respectively for span with highest elastic $d_m^{it}(t_1)$ (span AB). As stated earlier, this owes to the pronounced effect of t_1 on the shrinkage strain

$\varepsilon^{sh}(t_{21}, t_1)$. Further, as expected, there is a reduction in $d_m^t(t_{21})$ with increase in t_1.

3.2 Effect of magnitude of load

Three load cases are considered for beam EB3. In case 1, spans are subjected to only self-weight ($w = 2.31$ kN/m) whereas in cases 2 and 3, spans are subjected to $w = 9.00$ kN/m and 15.00 kN/m (service loads) respectively. The other data chosen is: $t_s = 14$ days; $t_1 = 14$ days, $f_{ck} = 30\,\text{N/mm}^2$ and RH =70%. For the chosen data, the values of $\phi(t_{21}, t_1)$ and $\varepsilon^{sh}(t_{21}, t_1)$ are 2.36 and 436.8×10^{-6} respectively.

Table 2. Effect of t_1 on instantaneous and total midspan deflections of beam EB3 for $w = 9.00$ kN/m, $f_{ck} = 30\,\text{N/mm}^2$ and RH=70%

Span	t_1 **(Days)**	**Midspan deflection (mm)**			**Time-dependent % change***
		Instantaneous, $d_m^{it}(t_1)$		**Total,** $d_m^t(t_{21})$ **(Including creep and shrinkage)**	
		Elastic (No cracking)	**Inelastic (Cracking)**		
(1)	(2)	(3)	(4)	(5)	(6)
AB	7	4.00	4.17	8.69	108.39
	14	3.93	4.02	7.71	91.79
	21	3.90	3.96	7.32	84.85
BC	7	0.94	1.07	0.86	-24.41
	14	0.92	0.99	0.80	-23.75
	21	0.91	0.96	0.78	-23.08
CD	7	1.96	1.89	3.02	59.79
	14	1.92	1.89	2.91	53.97
	21	1.91	1.89	2.85	50.79

*$100\times$ [column (5)-column (4)]/column (4)

It may be noted that, at the time of application of the load, cracking anywhere in beam is initiated at a load of 7.38 kN/m. The time-dependent analysis is carried out considering creep only and considering both creep and shrinkage.

The effect of magnitude of load on elastic M^{it} (t_1), inelastic M^{it} (t_1) and M^{t} (t_{21}) at supports B and C is shown in Table 3. It is seen from the table that elastic M^{it} (t_1) at a support generally decreases but may also increase when cracking at adjacent supports is higher. As expected, greater redistribution is observed when loading (and therefore, cracking) is higher. It may also be noted that the time-dependent change in inelastic M^t (t) is much smaller when only creep is considered. Significant variations occur for all the cases when shrinkage is also considered. Similar observations have also been made by Virtuoso and Vieira [2] and by Kwak and Seo [4] for precast prestressed concrete girder bridges. Further, as expected, no change due to creep is observed when only self-weight is acting since there is no cracking in this case and symmetrical change in curvature along the beam length does not result in additional bending moment.

Table 3. Effect of magnitude of load on instantaneous and total bending moments at supports of beam EB3 for $t_1 = 14$ days, $f_{ck} = 30\,\mathrm{N/mm^2}$ and RH=70%.

Support	**Load (kN/m)**	**Bending Moment (kN m)**				**Time-dependent % change**	
		Instantaneous, $M^{it}(t_1)$		**Total, $M^{t}(t_{21})$**			
		Elastic (No cracking)	**Inelastic (Cracking)**	**Creep only**	**Creep & shrinkage**	**Creep only#**	**Creep & shrinkage+**
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
B	2.31	11.89	11.89	11.89	50.11	0.00	321.45
	9.00	46.42	45.39	45.80	80.43	0.90	77.20
	15.00	77.37	68.52	71.80	102.61	4.82	42.91
C	2.31	8.92	8.92	8.92	37.58	0.00	321.30
	9.00	34.82	35.01	34.94	64.29	-0.19	83.63
	15.00	58.03	56.43	57.10	84.77	1.19	50.22

#100 × [column (5)-column (4)]/column (4) +100 × [column (6)-column (4)]/column (4)

It is also seen from Table 3 that the changes, due to creep and shrinkage, in inelastic $M^{it}(t_1)$ at a support are affected significantly by the magnitude of loading; these values for $w = 9.00\,\mathrm{kN/m}$ and $15.00\,\mathrm{kN/m}$ (service loads) being about 77% and 43% respectively at support B and about 84% and 50% respectively at support C.

Table 4 shows the effect of magnitude of load on elastic $d_m^{it}(t_1)$, inelastic $d_m^{it}(t_1)$ and $d_m^{t}(t_{21})$ for spans AB, BC and CD. In a span, elastic $d_m^{it}(t_1)$ generally increases due to cracking. Further it is observed that, due to creep and shrinkage, inelastic $d_m^{it}(t_1)$ may increase (span AB, CD) or decrease (span BC, w = 2.31 and 9.00 kN/m). Differing magnitudes of crack lengths and the influence of adjacent spans, result in this increase or decrease. An increase in crack length has two opposing effects: (i) increased portion with reduced flexural rigidity tending to increase the midspan deflections and (ii) increased portion with reduced creep and shrinkage tending to reduce the increase in the midspan deflections. In a span with highest elastic $d_m^{it}(t_1)$ (span AB), the percentage increase in inelastic $d_m^{it}(t_1)$ due to creep and shrinkage decreases with increase in magnitude of loading; these values for 9.00 kN/m and 15.00 kN/m (service loads) being about 76% and 50% respectively.

Table 4. Effect of magnitude of load on instantaneous and total midspan deflections of beam EB3 for $t_1 = 14$ days, $f_{ck} = 30\,\text{N/mm}^2$ and RH=70%.

Span	Load (kN/m)	Midspan deflection (mm)				Time-dependent % change	
		Instantaneous, $d_m^{it}(t_1)$		Total, $d_m^{t}(t_{21})$			
		Elastic (No cracking)	Inelastic (Cracking)	Creep only	Creep & shrinkage	Creep only[#]	Creep & shrinkage[+]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
AB	2.31	1.01	1.01	1.40	4.12	38.61	307.92
	9.00	3.93	4.02	5.52	8.64	37.31	114.93
	15.00	6.57	7.25	9.68	13.22	33.52	82.34
BC	2.31	0.24	0.24	0.33	-0.45	37.50	-287.5
	9.00	0.92	0.99	1.33	0.87	34.34	-12.12
	15.00	1.56	2.32	2.79	2.87	20.26	23.71
CD	2.31	0.49	0.49	0.68	1.07	38.78	118.37
	9.00	1.92	1.89	2.64	2.87	39.68	51.85
	15.00	3.19	3.44	4.63	5.22	34.59	51.74

#100 × [column (5)-column (4)]/column (4) +100 × [column (6)-column (4)]/column (4)

3.3 Effect of grade of concrete

As stated before, for concrete specimens, compressive strength has been recognized as one of the significant factors affecting creep and shrinkage. Three grades of concrete, M20, M30 and M40 ($f_{ck} = 20\,\mathrm{N/mm^2}$, $30\,\mathrm{N/mm^2}$ and $40\,\mathrm{N/mm^2}$ respectively) are considered. The other data chosen is: $w = 9.00$ kN/m; $t_s = 14$ days; $t_1 = 14$ days and RH = 70%. For $f_{ck} = 20\,\mathrm{N/mm^2}$, $30\,\mathrm{N/mm^2}$ and $40\,\mathrm{N/mm^2}$, the values of $\phi(t_{21}, t_1)$ are 3.20, 2.36 and 1.88 respectively and those of $\varepsilon^{sh}(t_{21}, t_1)$ are 502.7×10^{-6}, 436.8×10^{-6} and 382.2×10^{-6} respectively.

The effect of grade of concrete on inelastic $M^{it}(t_1)$ and $M^{t}(t_{21})$ at supports B and C is shown in Table 5. It is observed from the table that, inelastic $M^{it}(t_1)$ differ only slightly with grade of concrete. The slight difference is owing to different crack lengths resulting from different tensile strengths. Although as stated above, for concrete specimens, the compressive strength of concrete is one of the important factors affecting creep and shrinkage, the percentage changes, due to creep and shrinkage, in inelastic $M(t_1)$ do not differ much with grade of concrete; these changes for $f_{ck} = 20\,\mathrm{N/mm^2}$, $30\,\mathrm{N/mm^2}$ and $40\,\mathrm{N/mm^2}$ being about 72%, 77% and 80% respectively at support B and about 77%, 84% and 83% respectively at support C. Further, the values of $M^{t}(t_{21})$ generally increases with grade of concrete but may also decrease.

Table 5. Effect of grade of concrete on instantaneous and total bending moments at supports of beam EB3 for $w = 9.00$ kN/m, $t_1 = 14$ days and RH=70%.

Support	Concrete Grade	Bending Moment (kN m) – Instantaneous, $M^{it}(t_1)$: Elastic (No cracking)	Inelastic (Cracking)	Total, $M^{t}(t_{21})$ (Including creep and shrinkage)	Time-dependent % change
(1)	(2)	(3)	(4)	(5)	(6)
B	M20	46.42	44.01	75.90	72.46
	M30	46.42	45.39	80.40	77.13
	M40	46.42	46.22	83.07	79.73
C	M20	34.82	35.14	62.19	76.98
	M30	34.82	35.01	64.30	83.66
	M40	34.82	34.85	63.90	83.35

The effect of grade of concrete on elastic $d_m^{it}(t_1)$, inelastic $d_m^{it}(t_1)$ and $d_m^{t}(t_{21})$ for spans AB, BC and CD is shown in Table 6. As expected, elastic and inelastic $d_m^{it}(t_1)$ are higher for lower grade of concrete. The time-dependent change, due to creep and shrinkage, in inelastic $d_m^{it}(t_1)$ differ somewhat with grade of concrete; these change for $f_{ck} = 20\,\mathrm{N/mm^2}$, $30\,\mathrm{N/mm^2}$ and $40\,\mathrm{N/mm^2}$ are about 126% , 115% and 101% respectively for span with highest inelastic $d_m^{it}(t_1)$ (span AB). Further, the value of $d_m^{t}(t_{21})$ of span AB for M 40 is 1.22 times $d_m^{t}(t_{21})$ for M 20.

Table 6. Effect of grade of concrete on instantaneous and total midspan deflections of beam EB3 for $w=9.00\ \mathrm{kN/m}$, $t_1 = 14$ days and RH=70%.

Span	**Concrete Grade**	**Midspan deflection (mm)**			**Time-dependent % change**
		Instantaneous, $d_m^{it}(t_1)$		**Total, $d_m^{t}(t_{21})$ (Including creep and shrinkage)**	
		Elastic (No cracking)	**Inelastic (Cracking)**		
(1)	(2)	(3)	(4)	(5)	(6)
AB	M20	4.02	4.22	9.54	126.06
	M30	3.93	4.02	8.64	114.93
	M40	3.87	3.88	7.78	100.52
BC	M20	0.94	1.11	1.18	6.36
	M30	0.92	0.99	0.87	-12.12
	M40	0.91	0.92	0.60	-34.78
CD	M20	1.97	1.91	3.11	62.83
	M30	1.92	1.89	2.87	51.85
	M40	1.89	1.89	2.78	47.09

3.4 Effect of relative humidity

For concrete specimens, the relative humidity is another factor recognized as one of the significant factors affecting the creep and shrinkage. Three values of relative humidity (50%, 70% and 90%) are considered. The other data chosen is: $w = 9.00\ \text{kN/m}$; $t_s = 14$ days; $t_1 = 14$ days; and $f_{ck} = 30\ \text{N/mm}^2$. For RH = 50%, 70% and 90%, the values of $\phi(t_{21}, t_1)$ are 2.99, 2.36 and 1.71 respectively and those of $\varepsilon^{sh}(t_{21}, t_1)$ are 581.7×10^{-6}, 436.8×10^{-6} and 180.2×10^{-6} respectively.

The effect of relative humidity on $M^t(t_{21})$ at supports B and C is shown in Table 7. There is a significant effect of relative humidity on the time-dependent percentage change, in inelastic $M^{it}(t_1)$. For example, the change varies from about 99% to 39%, at support C, when RH increases from 50% to 90%. Also, $M^t(t_{21})$ increases significantly with decrease in relative humidity.

Table 7. Effect of relative humidity on total bending moments at supports of beam EB3 for $w = 9.00\ \text{kN/m}$, $t_1 = 14$ days and $f_{ck} = 30\ \text{N/mm}^2$

Support	**Relative Humidity**	**Bending Moment (kN m)**			**Time-dependent % change**
		Instantaneous, $M^{it}(t_1)$		**Total, $M^t(t_{21})$ (Including creep and shrinkage)**	
		Elastic (No cracking)	**Inelastic (Cracking)**		
(1)	(2)	(3)	(4)	(5)	(6)
B	50%	46.42	45.39	85.56	88.50
	70%	46.42	45.39	80.43	77.20
	90%	46.42	45.39	63.33	39.52
C	50%	34.82	35.01	69.72	99.14
	70%	34.82	35.01	64.29	83.63
	90%	34.82	35.01	48.60	38.82

The effect of relative humidity on $d_m^t(t_{21})$ for spans AB, BC and CD is shown in Table 8. Again, there is a significant effect of relative humidity on the time-dependent percentage change, in inelastic $d_m^{it}(t_1)$; the changes for span AB [span with highest elastic $d_m^{it}(t_1)$] being about 145% and 60% for RH= 50% and 90% respectively. Again, $d_m^t(t_{21})$ is also significantly more for less relative humidity.

Table 8. Effect of relative humidity on total midspan deflections of beam EB3 for $w = 9.00\ \text{kN/m}$, $t_1 = 14$ days and $f_{ck} = 30\ \text{N/mm}^2$.

Span	**Relative Humidity**	**Midspan deflection (mm)**			**Time-dependent % change**
		Instantaneous, $d_m^{it}(t_1)$		**Total, $d_m^t(t_{21})$ (Including creep and shrinkage)**	
		Elastic (No cracking)	**Inelastic (Cracking)**		
(1)	(2)	(3)	(4)	(5)	(6)
AB	50%	3.93	4.02	9.86	145.27
	70%	3.93	4.02	8.64	114.93
	90%	3.93	4.02	6.44	60.20
BC	50%	0.92	0.99	0.91	-8.08
	70%	0.92	0.99	0.87	-12.12
	90%	0.92	0.99	0.96	-3.03
CD	50%	1.92	1.89	3.02	59.79
	70%	1.92	1.89	2.87	51.85
	90%	1.92	1.89	2.63	39.15

3.5 Effect of Tension Stiffening

The data chosen for studying the effect of tension stiffening is: $w = 15.00$ kN/m; $t_s = 14$ days; $t_1 = 14$ days; $f_{ck} = 30\ \text{N/mm}^2$; and $\text{RH} = 70\%$. For the chosen data, the values of $\phi(t_{21}, t_1)$ and $\varepsilon^{sh}(t_{21}, t_1)$ are 2.36 and 436.8×10^{-6} respectively.

The effect of tension stiffening on inelastic $M^{it}(t_1)$ and $M^t(t_{21})$ at supports B and C is shown in Table 9. As expected, there is a greater change, due to cracking, in elastic $M^{it}(t_1)$ when tension stiffening is not considered. The effect of tension stiffening on the time-dependent percentage change in inelastic $M^{it}(t_1)$ is insignificant. For example, at support B, the time-dependent percentage change is about 53% when tension stiffening is not considered and about 50% when tension stiffening is considered.

Table 9. Effect of tension stiffening on instantaneous and total bending moments at supports of beam EB3 for $w = 15.00$ kN/m, $t_1 = 14$ days, $f_{ck} = 30$ N/mm^2 and RH=70%.

Support	**Tension Stiffening**	**Bending Moment (kN m)** Instantaneous, $M^{it}(t_1)$			**Time-dependent % change**
		Elastic (No cracking)	**Inelastic (Cracking)**	**Total, $M^{t}(t_{21})$ (Including creep and shrinkage)**	
(1)	(2)	(3)	(4)	(5)	(6)
B	Not considered	77.37	63.28	96.99	53.27
	Considered	77.37	68.52	102.61	49.75
C	Not considered	58.03	53.26	80.28	50.73
	Considered	58.03	56.43	84.77	50.22

Table 10. Effect of tension stiffening on instantaneous and total midspan deflections of beam EB3 for $w = 15.00$ kN/m, $t_1 = 14$ days, $f_{ck} = 30$ N/mm^2 and RH=70%.

Span	**Tension Stiffening**	**Midspan deflection (mm)** Instantaneous, $d_m^{it}(t_1)$			**Time-dependent % change**
		Elastic (No cracking)	**Inelastic (Cracking)**	**Total, $d_m^{t}(t_{21})$ (Including creep and shrinkage)**	
(1)	(2)	(3)	(4)	(5)	(6)
AB	Not considered	6.57	7.68	13.86	80.47
	Considered	6.57	7.25	13.22	82.34
BC	Not considered	1.56	2.99	4.02	34.45
	Considered	1.56	2.32	2.87	23.71
CD	Not considered	3.19	3.95	6.21	57.22
	Considered	3.19	3.44	5.22	51.74

The effect of tension stiffening on inelastic $d_m^{it}(t_1)$ and $d_m^{t}(t_{21})$ for spans AB, BC and CD is shown in Table 10. As expected, higher inelastic $d_m^{it}(t_1)$ is predicted for all the three spans, when tension stiffening is not considered. The effect of tension stiffening on the time-dependent percentage change in inelastic $d_m^{it}(t_1)$ is small for span of design significance [span AB, span with highest elastic $d_m^{it}(t_1)$]. The time-dependent percentage change for this span is about 80% when tension stiffening is not considered and about 82% when tension stiffening is considered.

3.6 Combination of rheological parameters

Now consider two combinations of extreme values of rheological parameters in the chosen range for the beam EB3 ($w = 9.00$ kN/m; $t_s = 7$ days). The data chosen for combination 1 is: $t_1 = 7$ days; $f_{ck} = 20\,\mathrm{N/mm^2}$; and $\mathrm{RH} = 50\%$. The data chosen for combination 2 is: $t_1 = 21$ days; $f_{ck} = 40\,\mathrm{N/mm^2}$; and $\mathrm{RH} = 90\%$. The values of $\phi(t_{21}, t_1)$ and $\varepsilon^{sh}(t_{21}, t_1)$ are obtained as 4.42 and 675.1×10^{-6} respectively for combination 1 and 1.35 and 136.1×10^{-6} respectively for combination 2.

The effect of two combinations of rheological parameters on elastic $M^{it}(t_1)$, inelastic $M^{it}(t_1)$ and $M^{t}(t_{21})$ at the supports B and C is shown in Table 11. It is observed that at both the supports, the time dependent percentage change, due to creep and shrinkage, for combination 2 is about three times the corresponding change for combination 1.

Table 11. Effect of combination of rheological factors on instantaneous and total bending moments at supports of beam EB3 for $w = 11.00$ kN/m.

Support	**Combination**	**Bending Moment (kN m)**			**Time-dependent % change**
		Instantaneous, $M^{it}(t_1)$		**Total, $M^{t}(t_{21})$ (Including creep and shrinkage)**	
		Elastic (No cracking)	**Inelastic (Cracking)**		
(1)	(2)	(3)	(4)	(5)	(6)
B	1	46.42	46.42	59.16	27.45
	2	46.42	43.07	79.52	84.63
C	1	34.82	34.82	44.39	27.48
	2	34.82	34.85	62.96	80.66

Table 12 shows the effect of two combinations on elastic $d_m^{it}(t_1)$, inelastic $d_m^{it}(t_1)$ and $d_m^{t}(t_{21})$ of spans AB, BC and CD. It is similarly observed that the time dependent percentage change in inelastic $d_m^{it}(t_1)$ for combination 2 is up to three times the corresponding change for combination 1(span AB) .

Table 12. Effect of combination of rheological factors on instantaneous and total midspan deflections of beam EB3 for $w=11.00$ kN/m

Span	**Combination**	**Midspan deflection (mm)**			**Time-dependent % change**
		Instantaneous, $d_m^{it}(t_1)$		**Total, $d_m^{t}(t_{21})$ (Including creep and shrinkage)**	
		Elastic (No cracking)	**Inelastic (Cracking)**		
(1)	(2)	(3)	(4)	(5)	(6)
AB	1	3.84	3.84	5.53	44.01
	2	4.09	4.37	10.55	141.42
BC	1	0.90	0.90	0.91	1.11
	2	0.96	1.22	1.19	-2.46
CD	1	1.88	1.88	2.44	29.79
	2	2.00	1.99	3.71	86.43

4. CONCLUSIONS

Systematic studies for the service load behavior of continuous composite beams with precast decks have been carried out using the hybrid procedure. The parameters whose effects have been studied on the bending moments at the supports and midspan deflections are t_1, w, f_{ck}, RH and tension stiffening. From the studies, following conclusions are drawn:

(a) The time-dependent changes in inelastic instantaneous moments at supports are primarily due to shrinkage.

(b) The age of concrete at the time of loading/ formation of composite section is found to have significant effect on the time-dependent changes, in bending moments at supports and some effect on the time-dependent changes in midspan deflections.

(c) The magnitude of loading has a significant effect on the time-dependent changes, in bending moments at supports and midspan deflections.

(d) The grade of concrete has a small effect on the time-dependent changes in bending moments at supports but some effect on the time-dependent changes in midspan deflections.

(e) The relative humidity has a significant effect on the time-dependent changes, in bending moments at supports and midspan deflections. Further, the total bending moments and midspan deflections increase significantly with decrease in relative humidity.

(f) The tension stiffening has a small effect on the time-dependent changes in bending moments at supports and the midspan deflections.

(g) The time-dependent changes, in bending moments at supports and midspan deflections, can vary significantly depending on the combination of the rheological parameters.

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NOTATIONS

A, B, I	= area, first moment of area and second moment of area;
E_c, E_s	= modulus of elasticity of concrete and steel respectively;
L	= span length;
M	= bending moment;
RH	= relative humidity;
d_m	= midspan deflection;
f_{ck}	= characteristic compressive strength of concrete;
f_{ct}	= tensile strength of concrete;
f_{ij}	= flexibility coefficients;
t_1	= age of concrete at time of loading/formation of composite section;
t_s	= time duration of curing;
w	= uniformly distributed load;
x	= crack length;
y	= $L - x$;
ϕ, ε^{sh}	= creep coefficient and shrinkage strain respectively;
ξ	= interpolation coefficient;
η	= $1-\xi$;
Subscript	
A, B	= ends A and B respectively;
cr, un	= cracked state and uncracked state respectively;
Superscript	
it, t	= instantaneous and total respectively;