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EVALUATING SHORT AND LONG TERM DEFLECTIONS OF BEAMS USING ACI 318 PROCEDURE

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Abstract- Deflections of reinforced concrete beams represent a serviceability issue that engineers may have trouble accurately calculating both short and long-term cases due to the currently available methods. Six different simply supported beam cases were analyzed using two approved methods by ACI 318 and compared with the results of SAP2000 to determine the differences in each method, and what the primary constituent in a reinforced concrete beam is in being able to meet the allowable deflection limit established by ACI 318. Ultimately, calculated deflection values have a high probability of being lower than actual values which may demonstrate that further research is needed in developing more precise methods for calculating deflections if they are to be critical in the design of a structure.

Keywords: Shrinkage, Creep, Deflection, Prediction Models.

1. INTRODUCTION

Most structures independent of the constructing material experience deflections due to the loading on the structure. In reinforced concrete members, deflections will increase with time because of the effects of shrinkage and creep of concrete. Excessive deflections can cause a structural failure of a member, but this will be out of the scope of this paper. The most common issues with deflections include potential damage to surrounding elements and structural members with noticeable deflections that are not aesthetically pleasing to the owner and building occupants [1]. It is the goal of a designer to limit deflections to prevent these types of serviceability issues.

There have always been discussions about the accuracy and methods that are used to calculate short and long-term deflections. Engineering mechanics has shown that the integration of beam curvature diagrams allows the ability to compute deflections and derive simple equations for maximum deflections based on different beam scenarios. While on paper this makes sense, the non-homogenous behavior of concrete requires these engineering mechanics formulas to be adjusted to try and accurately predict the deflection of reinforced concrete beams under sustained loading.

Factors such as beam cracking, creep, and shrinkage must be taken into account in order to predict deflections of reinforced concrete beams. Prediction models have been proposed such as ACI 209R-92 [2], CEB MC 1990 [3], B3 [4], GL2000 [5], CEB MC 2010 [6], B4 [7], and [8] to predict the shrinkage and creep of concrete structures. Also, several researchers investigated these models [9], [10], and [11]. The current research investigates the ACI 318 model which is based on the ACI 209R-92 prediction model, ACI 209.2R-08 [12], and ACI 209.1R-05 [13]. Several papers have been published on how to calculate deflections of reinforced concrete beams and ACI 318 has followed the recommendations of a few of these papers to lead to the current equations present in the code today. For instantaneous deflections (short-term), the maximum deflection is calculated in Equation (1) [14] as:

$$\Delta = \frac{kwL^4}{EI} \tag{1}$$

where, Δ is the maximum deflection, k is the beam stiffness, w is the factored load, L is the beam length, E is the beam modulus of elasticity, and I is the beam cross-sectional moment of inertia.

For reinforced concrete, modifications must be made to the beam modulus of elasticity and the beam cross-sectional moment of inertia. Reinforced concrete inherently cracks which leads to a reduced moment of inertia, but this topic has always been under discussion as to how to be taken into account. In 1963, reference [15] recommended the use of an effective moment of inertia (Ie) equation, to give better predictions of deflections, which was recommended in 1966 by the ACI Committee 435 and has been used since 1971 in ACI 318 [16]. Today, Branson's equation is equation 24.2.3.5a in ACI 318-14 [17]. Terms and definitions for equation 24.2.3.5a can be found in 24.2.3.5 of ACI 318-14. While short-term deflections are important in meeting allowable deflections by ACI 318, long-term deflections must also be calculated to determine if any serviceability issues will occur.

ACI 318 has developed a simplification to calculate long-term deflections which is to multiply the short-term deflection by a time-dependent $\lambda\Delta$ term. The original $\lambda\Delta$ term which was not time-dependent and was introduced by [18] and adopted into ACI 318-71 [19], has evolved with subsequent ACI 318 code editions. Reference [20] introduced a new time-dependent $\lambda\Delta$ term which was adopted by ACI 318-83 [21] and is now equation 24.2.4.1.1 in ACI 318-14. In the current ACI 318 method, long-term deflection is calculated without the reduction of the concrete elasticity. However, ACI 318 in section 24.2.4.1.1 allows a more comprehensive analysis to obtain long-term deflections where reductions of the concrete elasticity must be taken into account and will be further explained in the following section.

The effective moment of inertia equation present in ACI 318 has produced a wide variability in actual test data results [22-25]. Laboratory tests for simply supported beams revealed that about 90% probability that the percentage of actual deflections of beams to the calculated value will range between 80 and 130 [16]. This means there is a good probability of the actual deflections being higher than calculated and potentially exceeding the allowable limit if the calculated deflections are near the allowable limit. In another study, reference [26] reported a coefficient of variation of 25 to 50 percent for short-term deflections under a Monte Carlo simulation with most of the variation coming from actual values of flexural stiffness and concrete tensile strength [16]. A designer must therefore ensure that a beam design deflection is well below the allowable limit to avoid serviceability issues due to the inaccuracy of the current deflection methods. Even designing a beam not to crack can have substantial benefits.

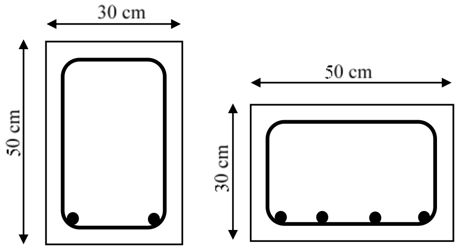
In the United States, serviceability allowable deflection limits are established by the American Concrete Institute (ACI) Committee 318. For this analysis, a 6 m simply supported beam with moderate loading was analyzed to determine if it can meet the deflection limit established by the ACI Committee 318 code, ACI 318-14. To provide a better understanding of what is critical in meeting the deflection limit in ACI 318 and to compare short and long-term deflections, the simply supported beam was altered to produce 6 separate cases while keeping the same amount of live and dead loads on the beam. The following alterations will be done to the beam: switching width and height dimensions, increasing the concrete compressive strength, and increasing steel percentage while remaining in a tension-controlled region. The remainder of this paper will present the deflection calculations of the beams using ACI 318, a comparison of the deflection results of the six beam cases based on ACI 318, and the structural engineering program SAP2000 [27], and final comments.

2. SOLUTION OF PROBLEM STATEMENT

All six beams have been designed according to ACI 318 and are able to meet a self-weight dead load of 3.532 kN/m and a live load of 7.297 kN/m. Table 1 shows the dimensions of the beams, concrete compressive strength, and amount of reinforcing steel present for all six cases. Figure 1 shows a schematic of the 2 beams designs that were used in the analysis. The allowable short-term deflection for a span length of 6 m allowed by ACI 318 Table 24.2.2 was determined to be 17 mm.

Table 1. Simply Supported Beams Properties

	b_w (cm)	h (cm)	fc' (MPa)	A_s (mm^2)	No. of bars
Beam 1	30	50	27.6	774	2 # 22
Beam 2	50	30	27.6	1548	4 # 22
Beam 3	30	50	41.4	774	2 # 22
Beam 4	50	30	41.4	1548	4 # 22
Beam 5	30	50	27.6	1548	4 # 22
Beam 6	50	30	27.6	2038	8 # 25



Beams 1, 3, 5 Beams 2, 4, 6

Figure 1. Beam Schematic

Short and long-term deflections were first calculated for all six beam cases by Section 24.2.3.5 of ACI 318. Long-term deflections were calculated at 3, 6, 12, 24, 48, and 60 months. An uncracked deflection was also calculated based on the gross moment of inertia of the beam cross-section. As allowed by 24.2.4.1.1 of ACI 318-14, all beams' cases were modeled in SAP2000 to obtain short and long-term deflections for comparison to ACI 318 hand methods. In order to take into account a cracked concrete section in SAP2000, the user must modify both the moment of inertia and modulus of elasticity. The effective moment of inertia from equation 24.2.3.5a of ACI 318-14 was used in SAP2000. Instead of modeling time in SAP2000 to obtain long-term deflections, an effective concrete modulus had to be used. ACI 209 has developed a time-dependent model for calculating the modulus of concrete under sustained loads due to creep. Table 2 shows the results of the effective modulus analysis using the recommendations of ACI 209. The effective modulus ($E'c$) values shown in Table 2 will be inputted into the SAP2000 model to obtain long-term deflections. The following assumptions were used: 7 days moist curing, 60% humidity, 12.7 cm slump, 50% fine aggregate content, and 5% air entrained. The results of deflection analysis will be addressed in section 3.

3. RESULTS

After performing all the required calculations from the problem statement, the numerical results are displayed for both the ACI 318 procedure and SAP2000 model in Figures 2 and 3 which show the deflections over time for both calculation methods for the 30 cm by 50 cm beams and the 50 cm by 30 cm beams, respectively. Overall, the results from both calculation methods coincided well with each other. For short-term deflections, SAP2000 gave deflections that were about 20 percent higher in all beam cases when compared to short-term deflections calculated by ACI 318. With long-term deflections though, the differences varied from less than 1 percent (Beam 3) to about 20 percent (Beam 2) between both methods. Only beams 1, 3, and 5 were able to meet the short-term allowable deflection limit of 17 mm.

Table 2. Effective Modulus of Concrete Analysis

Concrete Age (months)	Loading Time (days)	γ_{la}	γ_{λ}	γ_h	γ_s	γ_{ψ}	γ_{α}	γ_c	ν_u	*Ec* (MPa)	*Ct* (t)	*E'c*(t) (MPa)
For 27.6 MPa concrete												
3	83	0.735	0.868	0.772	1.16	1	1	0.569	1.34	24856	0.784	13931
6	173	0.677	0.868	0.772	1.16	1	1	0.524	1.23	24856	0.848	13453
12	358	0.623	0.868	0.772	1.16	1	1	0.483	1.13	24856	0.877	13245
24	723	0.574	0.868	0.772	1.16	1	1	0.445	1.04	24856	0.876	13248
48	1453	0.529	0.868	0.772	1.16	1	1	0.410	0.96	24856	0.855	13403
60	1818	0.515	0.868	0.772	1.16	1	1	0.399	0.94	24856	0.844	13477
For 41.4 MPa concrete												
3	83	0.735	0.868	0.772	1.16	1	1	0.569	1.34	30442	0.784	17062
6	173	0.677	0.868	0.772	1.16	1	1	0.524	1.23	30442	0.848	16476
12	358	0.623	0.868	0.772	1.16	1	1	0.483	1.13	30442	0.877	16222
24	723	0.574	0.868	0.772	1.16	1	1	0.445	1.04	30442	0.876	16226
48	1453	0.529	0.868	0.772	1.16	1	1	0.410	0.96	30442	0.855	16415
60	1818	0.515	0.868	0.772	1.16	1	1	0.399	0.94	30442	0.844	16506

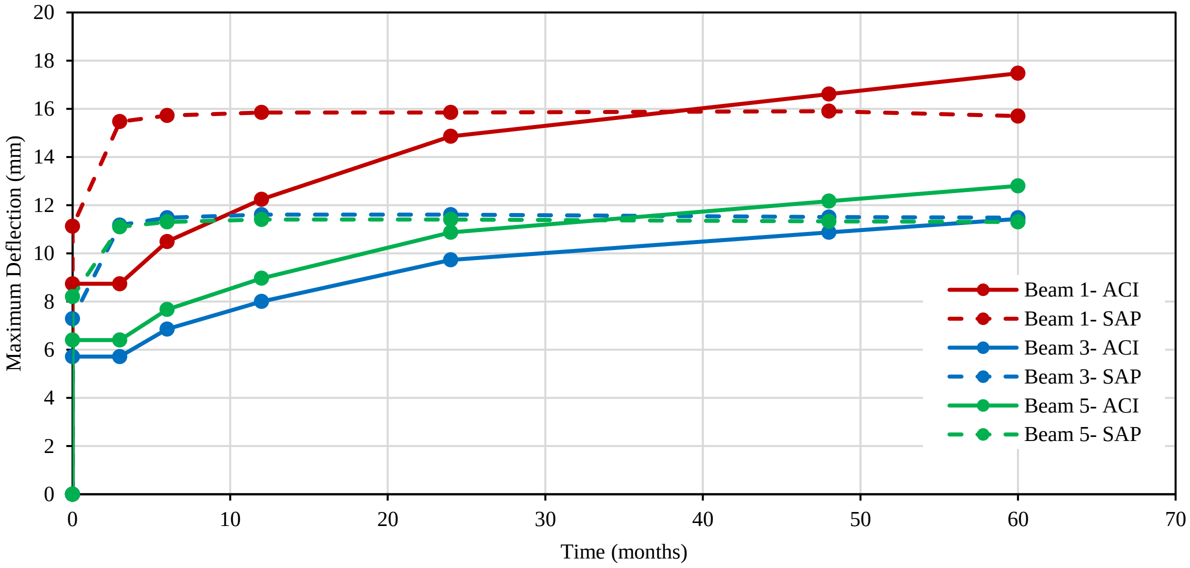


Figure 2. 30 cm by 50 cm Beam Deflections Results

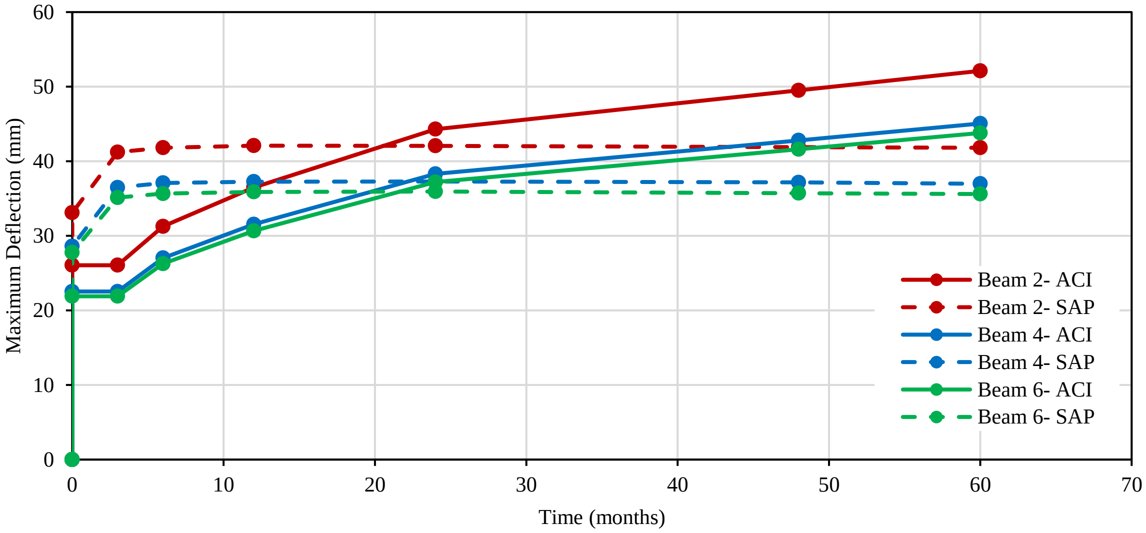


Figure 3. The 50 cm by 30 cm Beam Deflection Results

4. CONCLUSIONS

For all beam cases, the short-term deflections calculated from ACI 318 were less than those calculated from SAP2000. A few observations can be made from the deflection analysis to identify what is critical for controlling deflections in a beam in order to meet the allowable limit. A shallow wide beam is not ideal for controlling deflections as it reduces the moment of inertia which leads to larger deflections. Increasing the compressive strength of concrete or increasing the tensile steel help reduce deflections by increasing the cracking moment and the effective moment of inertia, respectively. Long-term deflections, however, resulted in the SAP2000 deflections being less than the ACI 318 deflections.

The differences in results between the ACI 318 and SAP2000 methods could be due to the approach both take in allowing the user to calculate deflections. The ACI 318 method for calculating long-term deflections relies on an empirically derived time-dependent equation that takes creep and shrinkage into account. This equation only allows the user to consider the effects of compression steel. In SAP2000 the user is allowed to modify the moment of inertia and modulus of elasticity to take into account time and effects of reinforcement because SAP2000 does not consider time or reinforcement for beams. With different approaches, both ACI 318 and SAP2000 model long-term deflections differently as evident in Figures 2 and 3. For the 5-year analysis, ACI 318 long-term deflections increased gradually with time while the SAP2000 long-term deflections immediately went to an ultimate value at 3 months and decreased slightly over time. The SAP2000 deflections decreased with time due to the modulus of elasticity increasing with time when calculated according to ACI 209. It appears from Table 2 that the effects of creep become negligible after more than two years because the modulus of elasticity no longer decreases but increases with time. In SAP2000, deflections went from short-term to long-term immediately once the initial inertia and elasticity values were changed. Even by modifying inertia and elasticity to consider time effects in SAP2000 and try to get gradual increases in deflections, the results did behave this way. While the deflection results for both methods were fairly close to each other, there has been a lot of debate about the actual accuracy of these methods for the real deflections.

Figures 2 and 3 display the uncracked short-term deflection and revealed that for all beam cases under these conditions, the allowable deflection limit was met. For a designer, a simple method to avoid deflection problems would be to ensure that the beam does not crack. A common procedure to identify whether the beam will become fully cracked is to see if the maximum positive moment of the beam will be subjected to twice the cracking moment of the beam [16]. By designing a beam not to crack, deflections can be controlled.

From this deflection analysis, a few methods were shown to help reduce deflections in order to avoid serviceability issues. The use of higher strength concrete, deeper beams, and an increase in the amount of tensile steel all helped in the reduction of deflections. Other methods such as the use of compression steel to reduce long-term deflections, fiber reinforcement, better curing methods to ensure sufficient concrete strength gain before loading, and to help reduce the effects of shrinkage and creep will all help in seeing a reduction in deflections.

Also, having a beam with no crack such as the case with prestressed beams will result in avoiding potential problems with deflections. Even with all these methods available to help control deflections, the current calculation procedures for measuring deflections can sometimes only provide an idea of what the actual deflection may be. Better methods for calculating deflections should be developed to help designers be able to rely on them comfortably.

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