

**Appendix B**

**Flexural Resistance of Members with  
Reinforcing Bars Lacking Well-Defined Yield  
Plateau**

## B.1 Introduction

The nominal moment capacity ( $M_n$ ) for non-prestressed members is commonly calculated by assuming a constant yield stress for the steel. For bars without a well-defined yield plateau, several approaches may be used to define the yield stress. In order to examine these methods, parametric studies were performed to assess the flexural resistance of members reinforced with various grades of steel reinforcement that do not have a well-defined yield plateau. The moment capacity was calculated by a number of methods ranging from simple design oriented procedures to complex fiber analysis. In fiber analysis, a cross section is divided into layers (fibers). The cross-sectional and material properties for each layer are defined, and strain compatibility between the layers is enforced. Realistic complete stress-strain relationships for concrete and steel layers are employed as opposed to simplified relationships typically used in the strain compatibility method. Therefore, complex analyses can be performed by fiber analysis technique. Comparing the results from the range of models made it possible to evaluate whether approximate methods are appropriate for members reinforced with reinforcing bars with no clear yield plateau and what material properties to use in these cases.

## B.2 Members and Parameters

Sections modeled were deck slabs, rectangular beams, and T-beams with varying steel types, amounts of steel, and concrete compressive strengths. The variables considered are summarized in Table B1. A total of 286 cross sections were analyzed.

**Table B1 Variables for Parametric Studies**

Parameter	Deck Slab	Rectangular Beam	T-Beam
Dimensions	7" and 10" thick	12"×16", 12"×28", 12"×36", 16"×28", 16"×36", and 16"×40"	12"×28", 12"×36", 16"×36", and 16"×40" with 96" effective flange width and 7" flange thickness
Concrete Strength, $f'_c$	5 ksi	5, 10, and 15 ksi	
Reinforcement Grades		A706, A496 & A82*, A955 (3 grades), and A1035	
Bar Sizes	#4, #5 and #6	#6 for 12" wide beams; and #8 for 16" wide beams. <i>All beams are assumed to have #4 stirrups with 2 inches of clear cover</i>	
Tension Reinforcement	Based on AASHTO spacing limitations	$A_{s,min}$ , $A_{s,max}$ , $0.5(A_{s,min} + A_{s,max})$	$A_{s,max}$ from corresponding rectangular beams

\* The properties established for A496 and A82 wire reinforcement were applied to #4, #5, #6, and #8 bars even though the bar diameters and areas are different from those for wire reinforcement.

The cross-sectional dimensions for the rectangular beams were chosen from the PCI Design Manual (2004). These sections were chosen to given representative cases of what may be used in design. The four largest sections were then used as the T-Beam dimensions. The flange thickness of the T-Beam was taken as 7 inches, a thickness commonly used for bridge decks. The effective flange width was determined from AASHTO §4.6.2.6. In this analysis, the effective span length was assumed to be 50 feet and the center-to-center spacing of the beams was taken as 8 feet. The controlling effective flange width was found to be 8 feet. Seven-inch

and ten-inch thick slabs were used in the analysis. The slab cross-sections were analyzed on a per foot basis.

Three different amounts of tensile reinforcement were incorporated in the rectangular beams. A maximum area of steel,  $A_{s,max}$  was determined based on the ACI 318-08 (2008) imposed minimum steel strain of 0.004. For a solid rectangular section,  $A_{s,max}$  is calculated from Eq. (B-1).

$$A_{s,max} = \frac{\gamma f'_c \beta_1 \left( \frac{3}{7} d_t \right) b}{f_y} \quad (B-1)$$

where  $d_t$  is the distance from the extreme compression fiber to the centroid of the extreme layer of longitudinal tension steel,  $b$  is the width of the beam,  $f_y$  is the nominal yield strength,  $f'_c$  is the concrete compressive strength,

$$\gamma = \begin{cases} 0.85 \text{ for } f'_c \leq 10 \text{ ksi} \\ 0.85 - 0.02(f'_c - 10) \geq 0.75 \text{ for } f'_c > 10 \text{ ksi} \end{cases} \quad \text{and}$$

$$\beta_1 = \begin{cases} 0.85 \text{ for } f'_c \leq 4 \text{ ksi} \\ 0.85 - 0.05(f'_c - 4) \geq 0.65 \text{ for } f'_c > 10 \text{ ksi} \end{cases}$$

A minimum area of steel,  $A_{s,min}$ , was established to satisfy AASHTO §5.7.3.3.2, i.e., to ensure that the flexural resistance with  $A_{s,min}$  is at least  $1.2M_{cr}$ , where  $M_{cr}$  is the cracking moment of the section. The average of  $A_{s,min}$  and  $A_{s,max}$  was also considered. Rectangular beams with  $A_{s,min}$  are in the tension-controlled region. Rectangular beams reinforced with  $A_{s,max}$  have the lowest steel strains allowed by ACI 318. The average of  $A_{s,min}$  and  $A_{s,max}$  results in cross-sections with strains between these limits. Because of the additional compression strength provided by the flanges of the T-beams, the calculated amount of steel required to provide  $A_{s,max}$  (i.e., to ensure a minimum strain of 0.004) was found to be excessive and impractical. Therefore, the values of  $A_{s,max}$  determined for the rectangular beams were provided in the corresponding T-beams. Nonetheless, the selected values of  $A_{s,max}$  resulted in members that fell well into the tension-controlled region. Providing more steel to obtain members in the transition region was impractical; hence, only one amount of reinforcement was used for the T-beams. The amount of steel provided in the slabs was determined based on spacing limitations prescribed in *AASHTO LRFD Bridge Design Specifications* §5.10.3.1, §5.10.3.2, and §5.10.8 (AASHTO 2008).

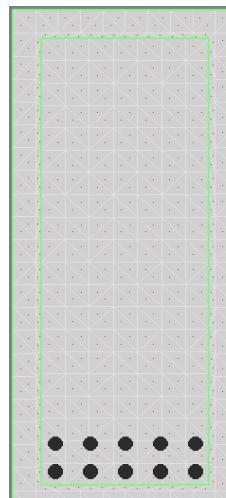
### B.3 Capacity Calculation Procedures

The nominal moment capacity of each section was calculated by a number of methods ranging from simple design oriented procedures to complex analysis techniques. The analyses included

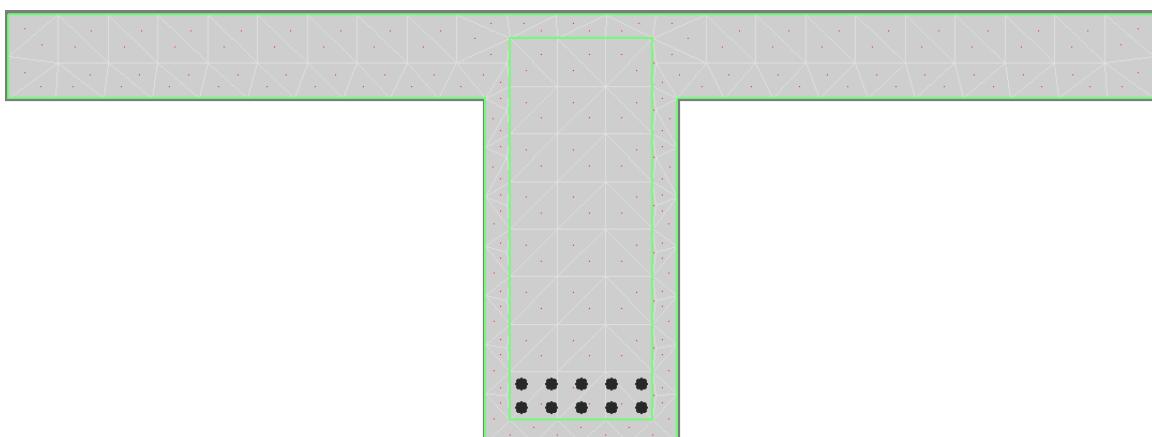
strain compatibility using different methods for modeling the steel stress-strain relationships, and fiber analysis.

### B.3.1 Fiber Analysis

In fiber analysis, a cross section is divided into layers (fibers). The cross-sectional and material properties for each layer are defined, and strain compatibility between the layers is enforced. A commercial computer program XTRACT (Imbsen, 2007) was used to perform the fiber analyses. The concrete was modeled using the unconfined concrete model proposed by Razvi and Saatcioglu (1999). The measured stress-strain data for each type of reinforcing steel were input directly into the XTRACT program. By using the experimentally obtained data, a more accurate capacity can be determined. Moment-curvature analyses were run in which the concrete strain was limited to 0.003, the level of strain used in the strain compatibility analyses. The results from fiber analyses are deemed to predict the most accurate flexural capacity. Figure B1 shows fiber models of representative rectangular and T-beams.



(a) Rectangular Beam

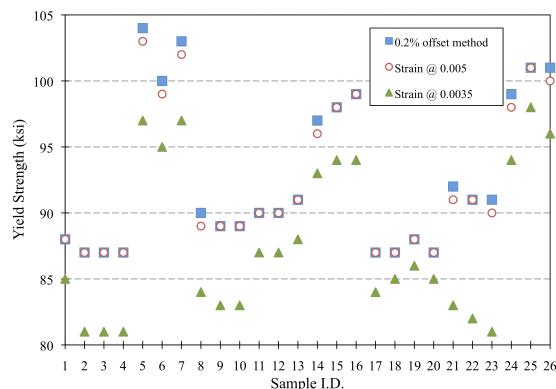


(b) T Beam

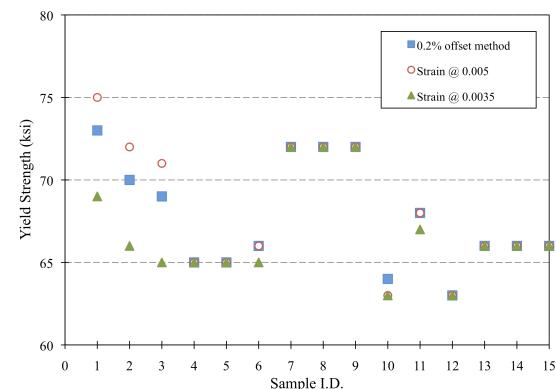
**Figure B1 Representative Fiber Models**

### B.3.2 Strain Compatibility

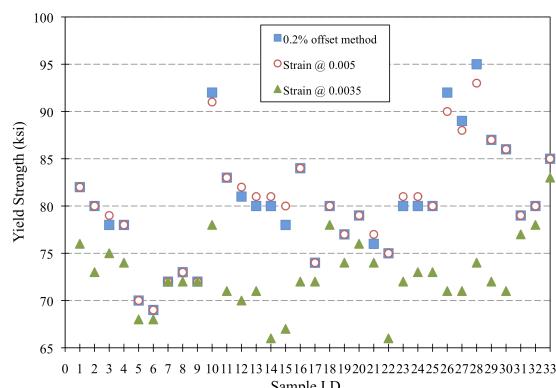
An Excel program (Shahrooz 2010) was used to compute flexural capacities based on strain compatibility analysis. The constitutive relationship of the reinforcing bars was modeled (a) as elastic-perfectly plastic with the yield point obtained by the 0.2% offset method and the stress at both strain = 0.0035 and strain = 0.005; and (b) by the Ramberg-Osgood function (Ramberg and Osgood, 1943) determined to best fit the experimentally obtained data (refer to Appendix A). The analyses utilized data from the measured stress-strain relationships of 98 samples of A706, A496 and A82, A955, and A1035 reinforcing bars. The yield strengths obtained from each method are summarized in Figure B2, and the averages and standard deviations are provided in Table B2.



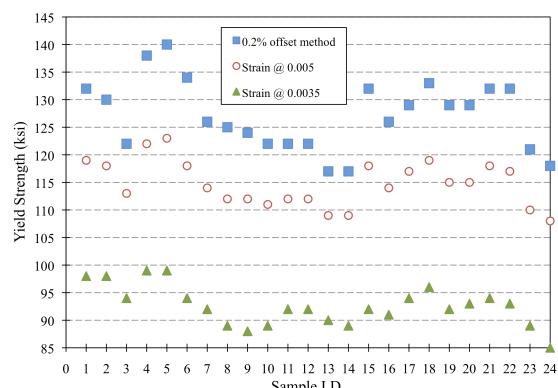
(a) A82 & A496



(b) A706



(c) A955



(d) A1035

Figure B2 Measured Yield Strengths

**Table B2 Average and Standard Deviations of  $f_y$  (ksi)**

Bar	Methodology for establishing the yield strength					
	0.2% offset method		Strain @ 0.005		Strain @ 0.0035	
	Avg. (ksi)	Std. Dev. (ksi)	Avg. (ksi)	Std. Dev. (ksi)	Avg. (ksi)	Std. Dev. (ksi)
A82 & A496	93	5.82	92	5.55	88	5.93
A706	68	3.30	68	3.83	67	3.05
A995	80	6.20	80	6.20	73	3.69
A1035	127	6.35	115	4.13	93	3.62

The values of the parameters for the Ramberg-Osgood function were calibrated to produce an analytical stress-diagram that would approximately represent the “average” of the measured stress-strain diagrams. The selected values of these parameters are summarized in Table B3.

**Table B3 Summary of Analysis Input Values**

Steel	A	B	C	$E_s$ (ksi)	$f_u$ (ksi)
A1035	0.0150	190	2.5	29000	160
A955	0.0120	350	7.20	29000	100
A706	0.0138	358	2.10	29000	100
A82 & A496	0.0150	310	3.90	29000	100

The equivalent stress block for high strength concrete, developed as part of NCHRP 12-64 (Rizkalla et al., 2007), was used to compute the concrete contribution to section behavior. The stress block parameters and modulus elasticity are summarized in Eq. (B-2).

$$\beta_1 = \begin{cases} 0.85 & \text{for } f'_c \leq 4 \text{ ksi} \\ 0.85 - 0.05(f'_c - 4) \geq 0.65 & \text{for } f'_c > 4 \text{ ksi} \end{cases}$$

$$(f'_c \text{ in ksi})$$

$$\gamma = \begin{cases} 0.85 & \text{for } f'_c \leq 10 \text{ ksi} \\ 0.85 - 0.02(f'_c - 10) \geq 0.75 & \text{for } f'_c > 10 \text{ ksi} \end{cases} \quad (B-2)$$

$$E_c = 310,000 K_1 (W_c)^{2.5} (f'_c)^{0.33} \text{ where } K_1 = 1; W_c = 0.15 \text{ kcf}$$

#### B.4 Results

The moment capacity for each section computed based on the aforementioned methods was normalized with the corresponding capacity calculated from the fiber analyses. The results for rectangular beams are presented in Table B4 for various grades of reinforcing bars. The corresponding values for T-beams and slabs are summarized in Tables B5 and B6, respectively.

**Table B4 Moment Capacities – Rectangular Sections**

**(a) A496-A82**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA 0.005/0.2%	RO/FA
						0.0035	0.005/0.2%	RO	FA		
5	12	16	192	3.08	0.0160	2436	2486	2406	2574	0.9464	0.9464
5	12	16	192	2.20	0.0115	1945	2046	2098	2178	0.8928	0.8928
5	12	16	192	1.32	0.0069	1277	1349	1458	1494	0.8545	0.8545
5	12	28	336	5.72	0.0170	8460	8672	8370	8949	0.9454	0.9454
5	12	28	336	3.52	0.0105	6051	6378	6692	6890	0.8782	0.8782
5	12	28	336	1.32	0.0039	2543	2695	2996	3048	0.8345	0.8345
5	12	36	432	7.48	0.0173	14502	14864	14332	15270	0.9497	0.9497
5	12	36	432	4.40	0.0102	9952	10493	11059	11380	0.8745	0.8745
5	12	36	432	1.32	0.0031	3388	3593	3999	4002	0.8466	0.8466
5	16	28	448	7.90	0.0176	12231	12539	12019	12780	0.9570	0.9570
5	16	28	448	5.53	0.0123	9368	9857	10136	10410	0.8999	0.8999
5	16	28	448	3.16	0.0071	5850	6184	6712	6811	0.8589	0.8589
5	16	36	576	10.27	0.0178	20742	21302	20423	21660	0.9576	0.9576
5	16	36	576	6.32	0.0110	14425	15202	15930	16270	0.8866	0.8866
5	16	36	576	3.16	0.0055	7872	8333	9234	9260	0.8501	0.8501
5	16	40	640	11.06	0.0173	25337	26311	25269	26690	0.9493	0.9493
5	16	40	640	7.11	0.0111	18160	19138	20043	20480	0.8867	0.8867
5	16	40	640	3.16	0.0049	8883	9407	10444	10490	0.8468	0.8468

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(a) A496-A82 (cont.)**

$f_c$ (ksi)	b (in)	h (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
10	12	16	192	4.40	0.0229	3484	3608	3534	3742	0.9310	0.9464
10	12	16	192	2.64	0.0138	2430	2567	2727	2793	0.8700	0.8928
10	12	16	192	1.32	0.0069	1331	1411	1569	1592	0.8362	0.8545
10	12	28	336	8.36	0.0249	12269	12667	12356	13080	0.9380	0.9454
10	12	28	336	5.28	0.0157	8999	9503	10029	10273	0.8760	0.8782
10	12	28	336	1.76	0.0052	3440	3648	4064	4127	0.8336	0.8345
10	12	36	432	11.00	0.0255	21064	21723	21175	22430	0.9391	0.9497
10	12	36	432	6.16	0.0143	14024	14821	15814	16170	0.8673	0.8745
10	12	36	432	1.76	0.0041	4566	4846	5400	5472	0.8344	0.8466
10	16	28	448	11.85	0.0265	18490	19054	18393	19410	0.9526	0.9570
10	16	28	448	7.90	0.0176	13699	14457	15115	15380	0.8907	0.8999
10	16	28	448	3.16	0.0071	6085	6449	7173	7194	0.8458	0.8589
10	16	36	576	15.80	0.0274	31921	32819	31619	33430	0.9549	0.9576
10	16	36	576	9.48	0.0165	21774	22995	24272	24660	0.8830	0.8866
10	16	36	576	3.16	0.0055	8106	8597	9574	9628	0.8419	0.8501
10	16	40	640	17.38	0.0272	39368	40638	39231	41400	0.9509	0.9493
10	16	40	640	10.27	0.0160	26525	28018	29672	30120	0.8807	0.8867
10	16	40	640	3.16	0.0049	9117	9673	10775	10830	0.8418	0.8468

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(a) A496-A82 (cont.)**

$f_c$ (ksi)	b (in)	h (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)				EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA			
15	12	16	192	5.72	0.0298	4229	4346	4280	4447	0.9511	0.9464	0.9624
15	12	16	192	3.52	0.0183	3156	3333	3531	3581	0.8812	0.8928	0.9862
15	12	16	192	1.32	0.0069	1345	1426	1588	1606	0.8373	0.8545	0.9885
15	12	28	336	10.56	0.0314	14615	15069	14827	15350	0.9521	0.9454	0.9659
15	12	28	336	6.16	0.0183	10373	10961	11677	11840	0.8761	0.8782	0.9863
15	12	28	336	1.76	0.0052	3463	3675	4097	4143	0.8359	0.8345	0.9888
15	12	36	432	14.08	0.0326	25100	25862	25427	26340	0.9529	0.9497	0.9653
15	12	36	432	8.80	0.0204	19019	20086	21210	21510	0.8842	0.8745	0.9860
15	12	36	432	2.64	0.0061	6706	7114	7927	7957	0.8428	0.8466	0.9963
15	16	28	448	15.01	0.0335	22440	23185	22518	23240	0.9656	0.9570	0.9690
15	16	28	448	9.48	0.0212	16224	17131	18059	18160	0.8934	0.8999	0.9944
15	16	28	448	3.16	0.0071	6142	6513	7254	7296	0.8418	0.8589	0.9942
15	16	36	576	19.75	0.0343	38614	39828	38676	39950	0.9666	0.9576	0.9681
15	16	36	576	11.85	0.0206	26890	28406	30099	30270	0.8883	0.8866	0.9944
15	16	36	576	3.16	0.0055	8163	8663	9654	9678	0.8435	0.8501	0.9976
15	16	40	640	22.12	0.0346	48138	49635	48240	49850	0.9657	0.9493	0.9677
15	16	40	640	12.64	0.0198	32298	34128	36316	36530	0.8842	0.8867	0.9941
15	16	40	640	3.16	0.0049	9174	9735	10856	10870	0.8440	0.8468	0.9988

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(b) A706**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
5	12	16	192	3.52	0.0183	2423	2502	2297	2590	0.9356	0.9660
5	12	16	192	1.76	0.0092	1468	1562	1650	1773	0.8281	0.8808
5	12	16	192	0.88	0.0046	771	824	941	1045	0.7379	0.7881
5	12	28	336	7.04	0.0210	8542	8740	8054	9151	0.9334	0.9551
5	12	28	336	3.52	0.0105	5380	5718	5972	6418	0.8383	0.8910
5	12	28	336	0.88	0.0026	1510	1615	2001	2159	0.6994	0.7481
5	12	36	432	7.92	0.0183	13626	14308	13245	14790	0.9213	0.9674
5	12	36	432	4.40	0.0102	8840	9401	9884	10620	0.8324	0.8852
5	12	36	432	0.88	0.0020	2003	2143	2770	2887	0.6937	0.7422
5	16	28	448	9.48	0.0212	12262	12636	11528	13000	0.9432	0.9720
5	16	28	448	5.53	0.0123	8354	8866	9025	9645	0.8662	0.9193
5	16	28	448	1.58	0.0035	2675	2859	3401	3692	0.7244	0.7744
5	16	36	576	11.85	0.0206	20654	21461	19578	21960	0.9405	0.9773
5	16	36	576	7.90	0.0137	15446	16378	16400	17600	0.8776	0.9306
5	16	36	576	2.37	0.0041	5271	5633	6599	7180	0.7342	0.7845
5	16	40	640	13.43	0.0210	25942	26832	24485	27510	0.9430	0.9753
5	16	40	640	7.90	0.0123	17659	18747	19188	20490	0.8618	0.9149
5	16	40	640	2.37	0.0037	5936	6343	7534	8226	0.7216	0.7711

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(b) A706 (cont.)**

$f_c$ (ksi)	b (in)	h (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO			
10	12	16	192	5.28	0.0275	3493	3601	3353	3672	0.9512	0.9806
10	12	16	192	2.64	0.0138	2150	2291	2435	2553	0.8422	0.8973
10	12	16	192	0.88	0.0046	790	845	1024	1102	0.7166	0.7666
10	12	28	336	8.80	0.0262	11460	12081	11304	12110	0.9464	0.9976
10	12	28	336	4.40	0.0131	6842	7295	7881	8132	0.8414	0.8971
10	12	28	336	1.32	0.0039	2280	2439	3062	3227	0.7064	0.7558
10	12	36	432	11.44	0.0265	19501	20542	19271	20860	0.9349	0.9847
10	12	36	432	6.16	0.0143	12401	13217	14149	14770	0.8396	0.8949
10	12	36	432	1.32	0.0031	3019	3230	4233	4300	0.7020	0.7513
10	16	28	448	14.22	0.0317	18378	19016	17443	19100	0.9622	0.9956
10	16	28	448	7.90	0.0176	12147	12929	13423	13930	0.8720	0.9281
10	16	28	448	2.37	0.0053	4046	4327	5207	5514	0.7337	0.7847
10	16	36	576	22.12	0.0384	31789	33442	30852	32970	0.9642	1.0143
10	16	36	576	11.06	0.0192	21906	23302	23885	24830	0.8822	0.9385
10	16	36	576	3.16	0.0055	7118	7614	9750	11680	0.6094	0.6519
10	16	40	640	21.33	0.0333	39776	40948	37576	41250	0.9643	0.9927
10	16	40	640	11.85	0.0185	26501	28201	29143	30240	0.8764	0.9326
10	16	40	640	3.16	0.0049	8004	8561	10447	10920	0.7330	0.7840

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(b) A706 (cont.)**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
15	12	16	192	6.16	0.0321	3944	3923	3798	4116	0.9582	0.9532
15	12	16	192	3.52	0.0183	2793	2976	3150	3219	0.8678	0.9244
15	12	16	192	0.88	0.0046	794	850	1073	1112	0.7142	0.7643
15	12	28	336	12.32	0.0367	14005	14521	13679	14440	0.9698	1.0056
15	12	28	336	7.04	0.0210	10188	10847	11339	11610	0.8775	0.9343
15	12	28	336	1.32	0.0039	2290	2451	3220	3239	0.7070	0.7566
15	12	36	432	15.84	0.0367	23876	24775	23356	24640	0.9690	1.0055
15	12	36	432	8.80	0.0204	16842	17938	18898	19330	0.8713	0.9280
15	12	36	432	1.76	0.0041	4024	4307	5638	5726	0.7028	0.7521
15	16	28	448	18.17	0.0406	22224	22924	21245	22420	0.9912	1.0225
15	16	28	448	11.06	0.0247	16251	17286	17663	18010	0.9023	0.9598
15	16	28	448	3.16	0.0071	5393	5768	6934	7212	0.7478	0.7998
15	16	36	576	23.70	0.0411	38127	39341	36431	38470	0.9911	1.0226
15	16	36	576	16.59	0.0288	27440	32729	30400	30530	0.8988	1.0720
15	16	36	576	3.95	0.0069	8911	9531	11540	11950	0.7457	0.7975
15	16	40	640	26.07	0.0407	47304	48934	45310	47850	0.9886	1.0227
15	16	40	640	14.22	0.0222	31422	33457	35013	35600	0.8826	0.9398
15	16	40	640	3.95	0.0062	10016	10717	13175	13600	0.7365	0.7880

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(c) A995**

$f_c$ (ksi)	b (in)	h (in)	$A_g$ (in $^2$ )	$A_s$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
					0.0035	0.005/0.2%	RO			
5	12	16	192	2.64	0.0138	1935	2228	2195	2326	0.9578
5	12	16	192	1.76	0.0092	1430	1667	1745	1836	0.9082
5	12	16	192	0.88	0.0046	750	883	978	1058	0.8345
5	12	28	336	5.28	0.0157	7128	8158	7942	8509	0.9588
5	12	28	336	3.52	0.0105	5242	6101	6332	6656	0.7876
5	12	28	336	1.32	0.0039	2176	2567	2896	3153	0.6902
5	12	36	432	7.04	0.0163	12354	14101	13679	14657	0.8429
5	12	36	432	4.4	0.0102	8614	10035	10465	10970	0.9148
5	12	36	432	1.32	0.0031	2894	3419	3955	4282	0.6758
5	16	28	448	7.9	0.0176	10771	12179	11640	12947	0.8319
5	16	28	448	3.95	0.0088	6184	7227	7637	8160	0.7579
5	16	28	448	1.58	0.0035	2600	3070	3511	3815	0.6816
5	16	36	576	10.27	0.0178	18277	20659	19771	21620	0.8454
5	16	36	576	6.32	0.0110	12501	14544	15032	15530	0.8049
5	16	36	576	1.58	0.0027	3460	4760	5464	5990	0.5775
5	16	40	640	11.06	0.0173	22270	25389	24410	26533	0.8393
5	16	40	640	7.11	0.0111	15739	18310	18914	20157	0.7808
5	16	40	640	2.37	0.0037	5771	6812	7781	8446	0.6833

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(c) A995 (cont.)**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
10	12	16	192	4.4	0.0229	3069	3483	3408	3585	0.8562	0.9716
10	12	16	192	2.64	0.0138	2093	2451	2577	2652	0.7893	0.9242
10	12	16	192	1.32	0.0069	1138	1343	1498	1565	0.7273	0.8582
10	12	28	336	8.8	0.0262	11184	12460	12106	12867	0.8693	0.9684
10	12	28	336	5.28	0.0157	7760	9076	9475	9739	0.7968	0.9319
10	12	28	336	1.76	0.0052	2937	3472	3990	4196	0.6999	0.8276
10	12	36	432	10.56	0.0244	18116	20750	20260	21183	0.8552	0.9795
10	12	36	432	6.16	0.0143	12072	14146	14945	15320	0.7880	0.9234
10	12	36	432	1.76	0.0041	3894	4609	5444	5725	0.6802	0.8050
10	16	28	448	11.85	0.0265	16145	18442	17728	18880	0.8552	0.9768
10	16	28	448	7.11	0.0159	10797	12234	12805	14130	0.7641	0.8658
10	16	28	448	2.37	0.0053	3933	4650	5363	5690	0.6912	0.8173
10	16	36	576	15.8	0.0274	27987	31765	30506	32513	0.8608	0.9770
10	16	36	576	9.48	0.0165	18778	19161	20136	23843	0.7876	0.8036
10	16	36	576	2.37	0.0041	5223	6181	7326	7715	0.6769	0.8011
10	16	40	640	17.38	0.0272	34508	39288	37810	40240	0.8576	0.9763
10	16	40	640	10.27	0.0160	22863	26755	27960	29137	0.7847	0.9183
10	16	40	640	3.16	0.0049	7780	9202	10400	10519	0.7396	0.8748
											0.9887

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(c) A995 (cont.)**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
15	12	16	192	5.28	0.0275	3606	4146	4078	4163	0.8664	0.9960
15	12	16	192	3.52	0.0183	2720	3183	3336	3385	0.8035	0.9404
15	12	16	192	1.32	0.0069	1148	1357	1548	1614	0.7115	0.8410
15	12	28	336	10.56	0.0314	12990	14578	14299	14710	0.8831	0.9911
15	12	28	336	6.16	0.0183	8931	10463	11035	11183	0.7986	0.9356
15	12	28	336	1.76	0.0052	2953	3496	4131	4317	0.6841	0.8097
15	12	36	432	13.2	0.0306	21616	24598	24187	24697	0.8753	0.9960
15	12	36	432	7.92	0.0183	15089	17682	18683	18883	0.7990	0.9364
15	12	36	432	2.64	0.0061	5721	6769	7877	8138	0.7030	0.8317
15	16	28	448	15.01	0.0335	19721	22382	21670	22450	0.8784	0.9970
15	16	28	448	7.9	0.0176	12091	14181	15056	15493	0.7804	0.9153
15	16	28	448	2.37	0.0053	3956	4683	5552	5852	0.6761	0.8002
15	16	36	576	19.75	0.0343	33936	38494	37231	37743	0.8991	1.0199
15	16	36	576	11.85	0.0206	23175	27122	28368	29120	0.7959	0.9314
15	16	36	576	3.16	0.0055	6963	8240	9759	10153	0.6858	0.8116
15	16	40	640	22.12	0.0346	42383	48007	46438	48063	0.8818	0.9988
15	16	40	640	11.85	0.0185	26397	30951	32771	33663	0.7841	0.9194
15	16	40	640	3.16	0.0049	7820	9260	11099	11520	0.6788	0.8038

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(d) A1035**

$f_c$ (ksi)	b (in)	h (in)	$A_g$ (in <sup>2</sup> )	$A_s$ (in <sup>2</sup> )	$\rho_s$	Moment Capacity (kips-in)				EPP/FA	EPP/FA	EPP/FA	0.2% offset	RO/FA	
						0.0035	0.005	0.20%	RO						
5	12	16	192	2.64	0.014	2452	2523	2444	2705	0.9066	0.9328	0.9328	0.9033		
5	12	16	192	2.20	0.011	2242	2448	2472	2253	0.8612	0.9405	0.9496	0.8655		
5	12	16	192	1.76	0.009	1920	2173	2335	2111	0.7880	0.8918	0.9580	0.8662		
5	12	28	336	4.40	0.013	8204	8660	8702	8334	0.8919	0.9415	0.9461	0.9061		
5	12	28	336	3.08	0.009	6292	7132	7669	7062	0.8139	0.7731	0.8763	0.9423	0.8677	
5	12	28	336	1.76	0.005	3926	4496	4869	5151	0.6604	0.7563	0.8189	0.8665		
5	12	36	432	5.28	0.012	13271	14565	14763	14015	15430	0.8601	0.9440	0.9568	0.9083	
5	12	36	432	3.52	0.008	9688	11017	11872	11389	13140	0.7373	0.8384	0.9035	0.8668	
5	12	36	432	1.76	0.004	5264	6045	6558	7238	8316	0.6330	0.7269	0.7886	0.8704	
5	16	28	448	6.32	0.014	11893	12255	12255	11824	12690	0.9372	0.9657	0.9657	0.9318	
5	16	28	448	3.95	0.009	8345	9474	10197	10081	11470	0.7276	0.8260	0.8890	0.8789	
5	16	28	448	3.16	0.007	6842	7802	8422	8899	9272	0.7379	0.8414	0.9083	0.9597	
5	16	36	576	7.90	0.014	19874	21000	21000	20166	22160	0.8968	0.9477	0.9477	0.9100	
5	16	36	576	5.53	0.010	15006	17004	18281	17634	19230	0.7804	0.8843	0.9506	0.9170	
5	16	36	576	3.16	0.005	9244	10582	11455	12944	13830	0.6684	0.7652	0.8283	0.9359	
5	16	40	640	8.69	0.014	24483	26049	26090	25002	27470	0.8913	0.9483	0.9498	0.9102	
5	16	40	640	5.53	0.009	17108	19438	20936	20963	22780	0.7510	0.8533	0.9190	0.9202	
5	16	40	640	3.16	0.005	10444	11971	12972	14995	15930	0.6556	0.7515	0.8143	0.9413	

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(d) A1035 (cont.)**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	Moment Capacity (kips-in)				EPP/FA 0.0035	EPP/FA 0.005	EPP/FA 0.2% offset	RO/FA	
					$\rho_g$	0.0035	0.005	0.20%					
10	12	16	192	3.52	0.018	3548	3804	3884	3686	4113	0.8627	0.9248	0.9444
10	12	16	192	2.64	0.014	2837	3229	3469	3172	3705	0.7657	0.8714	0.9363
10	12	16	192	1.76	0.009	2057	2357	2553	2620	3050	0.6745	0.7728	0.8371
10	12	28	336	6.60	0.020	12274	13135	13360	12718	14140	0.8681	0.9289	0.9448
10	12	28	336	4.40	0.013	9060	10334	11160	10560	12300	0.7366	0.8402	0.9073
10	12	28	336	1.76	0.005	4064	4680	5088	5770	6608	0.6149	0.7082	0.7699
10	12	36	432	8.80	0.020	21273	22615	22970	21892	24330	0.8743	0.9295	0.9441
10	12	36	432	5.28	0.012	14503	16568	17911	17406	20270	0.7155	0.8174	0.8836
10	12	36	432	1.76	0.004	5400	6228	6777	7921	8963	0.6025	0.6949	0.7561
10	16	28	448	9.48	0.021	18122	19200	19332	18462	19910	0.9102	0.9643	0.9710
10	16	28	448	6.32	0.014	13234	15081	16276	16009	16970	0.7798	0.8887	0.9591
10	16	28	448	3.16	0.007	7173	8245	8951	10548	10870	0.6599	0.7586	0.8235
10	16	36	576	12.64	0.022	31506	33087	33271	31845	35310	0.8923	0.9370	0.9422
10	16	36	576	7.90	0.014	21944	25030	27030	27061	29630	0.7406	0.8448	0.9123
10	16	36	576	3.16	0.005	9574	11025	11984	14712	15380	0.6225	0.7169	0.7792
10	16	40	640	13.43	0.021	38068	40826	41255	39250	43460	0.8759	0.9394	0.9493
10	16	40	640	7.90	0.012	24946	28506	30823	32006	34880	0.7152	0.8173	0.8837
10	16	40	640	3.16	0.005	10775	12416	13500	16811	17480	0.6164	0.7103	0.7723
													0.9617

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B4 Moment Capacities – Rectangular Sections (cont.)**

**(d) A1035 (cont.)**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	Moment Capacity (kips-in)				EPP/FA	EPP/FA	EPP/FA	RO/FA	
					$\rho_g$	0.0035	0.005	0.20%	RO	FA	0.0035	0.005	0.2% offset
15	12	16	192	4.40	0.023	4228	4579	4683	4470	4819	0.8773	0.9502	0.9718
15	12	16	192	3.08	0.016	3304	3767	4068	3834	4377	0.7548	0.8607	0.9293
15	12	16	192	1.76	0.009	2091	2402	2607	2816	3226	0.6481	0.7446	0.8080
15	12	28	336	8.36	0.025	14887	15982	16344	15599	16750	0.8888	0.9542	0.9758
15	12	28	336	5.28	0.016	10793	12326	13323	12901	14710	0.7337	0.8379	0.9057
15	12	28	336	1.76	0.005	4097	4725	5141	6011	6794	0.6030	0.6954	0.7566
15	12	36	432	11.44	0.026	25933	27537	28110	26864	28790	0.9008	0.9565	0.9764
15	12	36	432	6.60	0.015	17776	20317	21970	21549	24540	0.7244	0.8279	0.8953
15	12	36	432	1.76	0.004	5434	6273	6830	8228	9120	0.5958	0.6879	0.7489
15	16	28	448	11.85	0.026	22371	23919	24259	23086	24080	0.9290	0.9933	1.0074
15	16	28	448	7.11	0.016	15018	17158	18548	19175	19710	0.7619	0.8705	0.9411
15	16	28	448	3.16	0.007	7254	8353	9080	11150	11380	0.6374	0.7340	0.7979
15	16	36	576	15.80	0.027	38734	41104	41595	39650	42390	0.9138	0.9697	0.9813
15	16	36	576	9.48	0.016	26115	29826	32238	33128	35350	0.7388	0.8437	0.9120
15	16	36	576	3.16	0.005	9654	11133	12113	15373	15820	0.6103	0.7037	0.7657
15	16	40	640	17.38	0.027	47713	50986	51733	49256	52650	0.9062	0.9684	0.9826
15	16	40	640	10.27	0.016	31801	36341	39293	40787	43460	0.7317	0.8362	0.9041
15	16	40	640	3.16	0.005	10856	12524	13629	17517	17940	0.6052	0.6981	0.7597

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B5 Moment Capacities – T-beam Sections**

**(a) A496-A82**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in <sup>2</sup> )	$A_s$ (in <sup>2</sup> )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
5	12	28	924	5.72	0.0062	10316	10942	12190	12800	0.8059	0.8548
5	12	36	1020	7.48	0.0073	17658	18727	20867	21910	0.8059	0.8547
5	16	36	1136	10.27	0.0090	24888	26393	29372	30841	0.8070	0.8558
5	16	40	1200	11.06	0.0092	30127	31948	35564	37342	0.8068	0.8555
10	12	28	924	8.36	0.0090	14307	15185	16931	17777	0.8048	0.8542
10	12	36	1020	11.00	0.0108	24602	25378	28290	28720	0.8566	0.8837
10	16	36	1136	15.80	0.0139	36935	39176	43644	45826	0.8060	0.8549
10	16	40	1200	17.38	0.0145	45451	48208	53711	56396	0.8059	0.8548
15	12	28	924	10.56	0.0114	17192	18245	20350	21367	0.8046	0.8539
15	12	36	1020	14.08	0.0138	29814	30445	33942	34690	0.8594	0.8776
15	16	36	1136	19.75	0.0174	44662	47370	52776	55415	0.8060	0.8548
15	16	40	1200	22.12	0.0184	55808	59189	65946	69244	0.8060	0.8548

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B5 Moment Capacities –T-beam Sections (cont.)**

**(b) A706**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
5	12	28	924	6.16	0.0067	9633	10307	12847	13340	0.7221	0.7726
5	12	36	1020	8.80	0.0086	17781	19012	23395	24680	0.7204	0.7703
5	16	36	1136	11.85	0.0104	24865	26583	31598	33020	0.7530	0.8050
5	16	40	1200	13.43	0.0112	31371	33534	39784	41440	0.7570	0.8092
10	12	28	924	9.68	0.0105	14043	15028	18685	19120	0.7345	0.7860
10	12	36	1020	13.20	0.0129	24797	26531	32735	34160	0.7259	0.7767
10	16	36	1136	18.96	0.0167	37622	40232	47660	50110	0.7508	0.8029
10	16	40	1200	21.33	0.0178	47232	50511	59784	62490	0.7558	0.8083
15	12	28	924	12.32	0.0133	16789	17963	22322	22570	0.7439	0.7959
15	12	36	1020	15.84	0.0155	28386	30373	37851	38760	0.7324	0.7836
15	16	36	1136	23.70	0.0209	45171	48296	57397	59590	0.7580	0.8105
15	16	40	1200	26.07	0.0217	55687	59539	70919	73160	0.7612	0.8138
											0.9694

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B5 Moment Capacities –T-beam Sections (cont.)**

**(c) A995**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in <sup>2</sup> )	$A_s$ (in <sup>2</sup> )	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
						0.0035	0.005/0.2%	RO	FA		
5	12	28	924	5.28	0.0057	8233	8469	9866	10290	0.8001	0.8231
5	12	36	1020	7.04	0.0069	14315	14727	17095	18030	0.7940	0.8168
5	16	36	1136	10.27	0.0090	21261	21870	24298	26280	0.8090	0.8322
5	16	40	1200	11.06	0.0092	25729	28189	31208	31690	0.8119	0.8895
10	12	28	924	8.8	0.0095	12718	13084	15060	15640	0.8132	0.8366
10	12	36	1020	10.56	0.0104	20328	20915	24413	25240	0.8054	0.8287
10	16	36	1136	15.8	0.0139	31516	32422	36097	38950	0.8091	0.8324
10	16	40	1200	17.38	0.0145	38779	39893	44493	47510	0.8162	0.8397
15	12	28	924	10.56	0.0114	14659	15085	17523	17870	0.8203	0.8441
15	12	36	1020	13.2	0.0129	24221	24925	29172	29830	0.8120	0.8356
15	16	36	1136	19.75	0.0174	38104	39197	43789	46410	0.8210	0.8446
15	16	40	1200	22.12	0.0184	47612	48978	54692	57380	0.8298	0.8536
											0.9532

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B5 Moment Capacities –T-beam Sections (cont.)**

**(d) A1035**

$f_c$ (ksi)	$b$ (in)	$h$ (in)	$A_g$ (in $^2$ )	$A_s$ (in $^2$ )	$\rho_g$	Moment Capacity (k-in.)			EPP/FA	EPP/FA	EPP/FA 0.2% offset	RO/FA
						0.0035	0.005	0.20%				
5	12	28	924	5.28	0.0057	11413	13162	14314	18475	18770	0.6080	0.7013
5	12	36	1020	5.28	0.0052	15423	17807	19382	25604	25620	0.6020	0.6950
5	16	36	1136	7.9	0.0070	23325	26879	29228	37345	38400	0.6074	0.7000
5	16	40	1200	7.9	0.0066	26319	30352	33020	42742	43420	0.6062	0.6990
10	12	28	924	7.04	0.0076	14769	17054	18565	24386	25606	0.5768	0.6660
10	12	36	1020	7.04	0.0069	20118	23246	25320	33570	35248	0.5708	0.6595
10	16	36	1136	11.85	0.0104	34114	39359	42839	55147	56290	0.6060	0.6992
10	16	40	1200	11.85	0.0099	38618	44576	48522	63282	63770	0.6056	0.6990
15	12	28	924	8.8	0.0095	17748	20496	22314	29297	30762	0.5770	0.6663
15	12	36	1020	8.8	0.0086	24432	28242	30758	40783	42822	0.5705	0.6595
15	16	36	1136	15.8	0.0139	43977	50730	55213	70775	72260	0.6086	0.7020
15	16	40	1200	15.8	0.0132	49981	57230	62259	78429	82250	0.6077	0.6958

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B6 Moment Capacities –Slabs**

**(a) A496-A82**

Slab	$A_s = A_{s'}$	$A_s + A_{s'}$	$A_g$	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
					0.0035	0.005/0.2%	RO	FA	0.0035	0.005/0.2%
7" Slab (#4 bars)	0.52	1.05	84	0.012	207	207	222	303	0.6850	0.6850
7" Slab (#5 bars)	0.92	1.84	84	0.022	300	300	304	439	0.6830	0.6830
7" Slab (# 6 bars)	1.33	2.65	84	0.032	370	370	353	529	0.6991	0.6991
10" Slab(#4 bars)	0.39	0.79	120	0.007	266	278	300	402	0.6635	0.6932
10" Slab (#5 bars)	0.61	1.23	120	0.010	377	394	421	618	0.6093	0.6383
10" Slab (#6 bars)	0.88	1.77	120	0.015	501	526	556	820	0.6106	0.6407
										0.6773

**(b) A706**

Slab	$A_s = A_{s'}$	$A_s + A_{s'}$	$A_g$	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
					0.0035	0.005/0.2%	RO	FA	0.0035	0.005/0.2%
7" Slab (#4 bars)	0.34	0.67	84	0.008	143	150	152	161	0.8903	0.9356
7" Slab (#5 bars)	0.57	1.13	84	0.013	202	210	209	225	0.8976	0.9338
7" Slab (# 6 bars)	0.88	1.77	84	0.021	266	277	264	292	0.9115	0.9512
10" Slab(#4 bars)	0.26	0.52	120	0.004	170	181	201	211	0.8052	0.8578
10" Slab (#5 bars)	0.43	0.87	120	0.007	262	275	295	311	0.8426	0.8843
10" Slab (#6 bars)	0.62	1.25	120	0.010	345	363	386	406	0.8502	0.8943
										0.9513

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

**Table B6 Moment Capacities –Slabs**

**(c) A995**

Slab	$A_s = A_{s'}$	$A_s + A_{s'}$	$A_g$	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	RO/FA
					0.0035	0.005/0.2%	RO	FA	0.0035	0.005/0.2%
7" Slab (#4 bars)	0.52	1.05	84	0.012	189	192	192	201	0.9377	0.9533
7" Slab (#5 bars)	0.92	1.84	84	0.022	270	275	274	288	0.9385	0.9559
7" Slab (# 6 bars)	1.33	2.65	84	0.032	339	346	333	356	0.9529	0.9713
10" Slab(#4 bars)	0.39	0.79	120	0.007	238	243	249	261	0.9111	0.9293
10" Slab (#5 bars)	0.61	1.23	120	0.010	334	341	348	365	0.9127	0.9323
10" Slab (#6 bars)	0.88	1.77	120	0.015	441	453	462	485	0.9106	0.9350

**(d) A1035**

Slab	$A_s = A_{s'}$	$A_s + A_{s'}$	$A_g$	$\rho_g$	Moment Capacity (kips-in)			EPP/FA	EPP/FA	EPP/FA	RO/FA
					0.0035	0.20%	RO	FA	0.0035	0.0050	0.2% offset
7" Slab (#4 bars)	1.18	2.36	84	0.028	382	382	373	403	0.9485	0.9485	0.9485
7" Slab (#5 bars)	1.84	3.68	84	0.044	434	434	436	487	0.8914	0.8914	0.9267
7" Slab (# 6 bars)	2.65	5.30	84	0.063	541	480	489	572	0.9443	0.8391	0.8946
10" Slab(#4 bars)	0.67	1.35	120	0.011	466	525	565	606	0.7354	0.8290	0.8911
10" Slab (#5 bars)	1.05	2.10	120	0.018	669	757	814	799	0.7816	0.8838	0.9511
10" Slab (#6 bars)	1.77	3.53	120	0.029	1024	1102	1102	1182	0.8660	0.9319	0.8914

0.0035 = yield stress is the stress corresponding to strain equal to 0.0035

0.005 = yield stress is the stress corresponding to strain equal to 0.005

0.2% = yield stress defined by the 0.2% offset method

RO = steel stress-strain diagram is modeled by the Ramberg-Osgood function

EPP = elastic-perfectly plastic analysis

FA = fiber analysis

Table B7 summarizes the average, minimum, maximum, and standard deviation of the results of the strain compatibility analyses conducted using the Ramberg-Osgood function for the rectangular beams, T-beams, and slabs for all the steel types and the selected concrete strengths considered. The computed capacities are below or nearly equal to those calculated based on fiber analysis, i.e., the ratios are close to or slightly less than unity. The exceptional estimates of the expected capacity based on the Ramberg-Osgood function in conjunction with strain compatibility analysis should be expected as this function closely replicates the measured stress-strain curves that were used in the fiber analyses. Additionally, the good correlation suggests that well-established procedures can be used to calculate the flexural capacity of members reinforced with bars that do not have a well-defined yield plateau so long as the stress-strain relationship is modeled accurately.

**Table B7 Ratios of Flexural Capacity Determined from Ramberg-Osgood Strain Compatibility Analysis to that Determined from Fiber Model**

Section	Average	Minimum	Maximum	Standard Deviation
Rectangular	0.944	0.835	0.999	0.037
T-beam	0.962	0.925	0.999	0.017
Slab	0.875	0.668	0.955	0.107

Note: Ratio less than 1 is conservative.

In spite of its success, the use of Ramberg-Osgood functions is not appropriate for routine design. Most designers are familiar with using a single value of reinforcing bar yield,  $f_y$ , i.e., an elastic-plastic analysis with a value of yield strength. For this reason, the results from strain compatibility analyses with the yield strength taken at strain = 0.0035, strain = 0.005, and 0.2% offset method are examined further. The average, minimum, maximum, and standard deviation of the ratio of the computed capacities to the capacity based on fiber analysis are summarized in Table B8.

**Table B8 Ratios of Rectangular Beam Flexural Capacity Calculated from Elastic-Plastic Analyses to that from Fiber Model**

Yield Point	$f_c$ (ksi)	Average	Minimum	Maximum	Standard Deviation
@ Strain = 0.0035	5	0.820	0.578	0.958	0.094
	10	0.815	0.603	0.964	0.100
	15	0.825	0.596	0.991	0.108
@ Strain = 0.005	5	0.884	0.727	0.977	0.070
	10	0.880	0.652	1.014	0.084
	15	0.891	0.688	1.072	0.092
0.2% offset	5	0.909	0.789	0.966	0.057
	10	0.884	0.756	0.971	0.075
	15	0.890	0.749	1.007	0.092

Note: Ratio less than 1 is conservative.

For the beams having 5 ksi concrete, the ratios from any of the values of yield strength are less

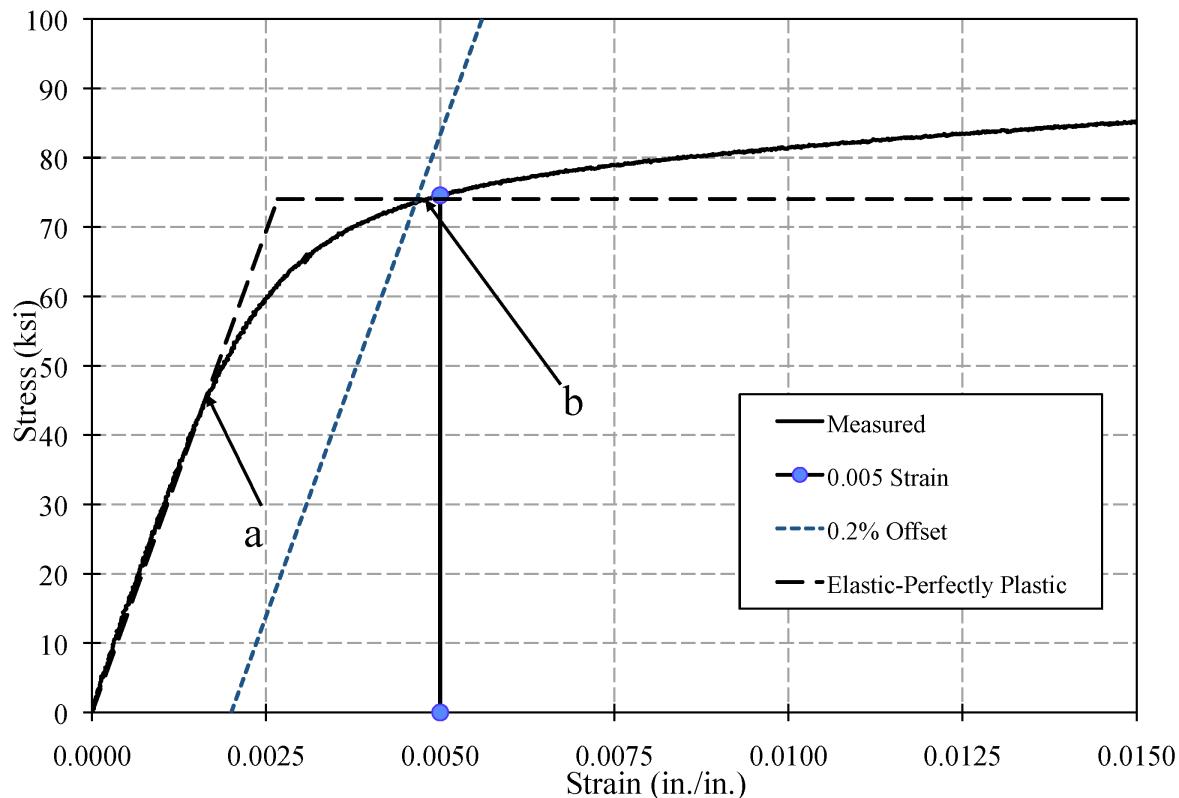
than unity, i.e., the flexural strength can be conservatively computed based on any of three methods used to establish the yield strength. The same conclusion cannot be drawn for the beams with 10 and 15 ksi concrete. For a limited number of cases (given in Table B9) involving relatively large longitudinal reinforcement ratios ( $\rho_g$ ), the strength ratio exceeds unity if the capacity is based on an idealized elastic-perfectly plastic stress-strain relationship with the yield strength taken as the stress at a strain of 0.005 or determined based on the 0.2% offset method. That is, the yield strengths based on these two methods may result in slightly unconservative estimates of the expected capacity in cases with large reinforcement ratios and high-strength concrete.

**Table B9 Cases where Elastic-Plastic Analysis Overestimate Flexural Capacity**

Steel Type	$f_c$ (ksi)	$\rho_g$	Ratio
A706	10	3.84%	1.014
	15	3.67%	1.006
	15	3.67%	1.005
	15	4.06%	1.022
	15	4.11%	1.023
	15	2.88%	1.072
	15	4.07%	1.023
A995	15	3.43%	1.020
A1035	15	2.65%	1.007

The aforementioned behavior can be understood with reference to Figure B3, which depicts a measured stress-strain curve for an A706 bar along with the idealized elastic-perfectly plastic model based on the yield strength taken as the value determined from the 0.2% offset method and the stress at strain equal to 0.005. Note that in this case, these two methods result in the same values of yield strength. Between points "a" and "b" (see Figure B3) the elastic-perfectly plastic model deviates from the measured stress-strain diagram. The stresses based on this model exceed the actual values. For strains below point "a" and strains above "b", the stresses from the idealized model are equal to or less than the measured values. As the reinforcement ratio increases, i.e., as the amount of longitudinal steel becomes larger, the strain in the reinforcing bars at any given applied moment will become less. For the cases involving the large reinforcement ratios shown in Table B9, the steel strains fall between points "a" and "b" when the extreme concrete compressive stress of 0.003 is reached. Thus, the higher yield strength from the elastic-perfectly plastic model overestimates the actual flexural capacity.

In the case of T-beams and slabs, any of the aforementioned methods for establishing the yield strength result in acceptable, conservative flexural capacities. As evident from Table B10, the ratios of the flexural capacity based on simple elastic-perfectly plastic models to the corresponding values from fiber analysis are less than one. The trend of data is expected, as the longitudinal strain in a T-beam will be higher than that in an equivalent rectangular beam because of the additional compressive force that can be developed in the flange. The smaller depths of the slabs will also increase the strain in the longitudinal bars. In both these cases, the larger strains will correspond to cases beyond the strain at point "b" in Figure B3, where the elastic-plastic assumption underestimates the real stress developed in the steel.



**Figure B3 Typical Measured Stress-Strain Diagram and Elastic-Perfectly Plastic Model**

**Table B10 Ratios of T-Beam and Slab Flexural Capacity Calculated from Elastic-Plastic Analyses to that from Fiber Model**

<b>T-Beams</b>				
Yield Point	Average	Minimum	Maximum	Standard Deviation
@ Strain =0.0035	0.741	0.571	0.859	0.091
@ Strain =0.005	0.795	0.659	0.890	0.069
0.2% offset	0.748	0.718	0.764	0.019
<b>Deck Slabs</b>				
Yield Point	Average	Minimum	Maximum	Standard Deviation
@ Strain =0.0035	0.828	0.609	0.953	0.115
@ Strain =0.005	0.854	0.638	0.971	0.113
0.2% offset	0.909	0.839	0.951	0.043

Note: Ratio less than 1 is conservative.

## B.5 Summary

Considering the presented results, the use of Ramberg-Osgood functions for defining the stress-strain characteristics of reinforcing bars without a well-defined yield plateau will produce the

most accurate estimate of the actual flexural capacity. The use of the strain compatibility approach assuming an elastic-perfectly plastic steel stress strain relationship having a yield stress defined at either a strain of 0.0035 or 0.005 ensures that the flexural capacity is computed conservatively and reliably for the range of reinforcement ratios and concrete compressive strengths encountered in practice. However, for beams with reinforcement ratios exceeding 3%, the definition of the yield stress at a strain of 0.0035 is more appropriate. The latter approach is consistent with the currently prescribed ACI 318 (ACI 318-08, 2008) approach. The use of the stress at 0.0035 strain effectively ensures that the steel strain under the design condition is beyond point "b", shown in Figure B3. Recall that this is enforced in the design approach through the definition of  $A_{s \text{ max}}$  as the steel content that allows a steel strain of 0.004 to be achieved.