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Recommended Citation

Roure, Francesc; Peköz, Teoman; Somalo, M. Rosa; Bonada, Jordi; Pastor, M. Magdalena; Casafont, Miquel; and Crews, James, "Industrial Cold-Formed Steel Rack Column Base Fixity and Strength" (2016). *International Specialty Conference on Cold-Formed Steel Structures*. 2.
https://scholarsmine.mst.edu/isccss/23iccfss/session6/2

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Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
Baltimore, Maryland, U.S.A, November 9 & 10, 2016

Industrial Cold-Formed Steel Rack Column Base Fixity and Strength

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Abstract

This paper summarizes the testing done at the Universitat Politècnica de Catalunya, Barcelona, Spain and the possible use of the results in design for column base stiffness and strength. The test setup and procedure are adopted in the European rack design standards.

Introduction

The fixity of the column bases is an important parameter in the design of industrial cold-formed steel pallet racks. The strength and stiffness of the column base depends on the details of connection and the magnitude of the axial load in the column. The design of industrial storage racks is carried out according to the ANSI MH16.1: 2012 [1] in the United States and EN 15512 document [2] in Europe. Neither of these documents provides comprehensive provisions for the calculation of the stiffness and strength of the column base connection. The details of column base plate connection in the United States and Europe are significantly different. In the United States the base plate is welded directly to the column and the base plate is in general anchored to the underlying floor. In Europe the columns are in general bolted to the base plates through various details. The subject of base plate testing and design is well covered for an Australian type of base plate which is similar to a European one in Gilbert and Rasmussen [3]. Baldassino, et al [4].

Attempts have been made to reach a comprehensive analytical (finite element) representation of the stiffness and strength of all types of column bases by the authors, Gilbert and Rasmussen [3]. Baldassino, et al [4]. Due to the variety of baseplate geometries, complexity of the behavior and the parameters involved, it is preferable to carry out tests to aid in design.

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Test fixture and procedure

The present RMI Specification does not have a test procedure for column bases. Document EN 15512:2009 has a test procedure that has been used and discussed in Gilbert and Rasmussen [3] and Baldassino, et al [4]. Some improvements to the test setup and procedures of EN 15512:2009 are proposed in these documents. A new version of EN 15512:2009 that will be available this year as a prEN 15512:2016 (prenorm) contains some improvements to the test setup and procedure of EN 15512:2009 as well as an alternate test setup will be given in prEN 15512:2016.

The alternate test setup and procedure described in Roure, et al. [5] developed at the Universitat Politècnica de Catalunya, Barcelona, Spain was used in this study. The alternate setup shown in Figs. 1 and 2 consist of a segment of the column with a base plate attached to a representative concrete block. The moment at the base plate is provided by a lateral force on the free end of the column segment. The axial load is kept constant during the test and the moment on the base plate is determined including the second order effects due to the axial load and the lateral deflection.

The alternate testing setup was much simpler to align and monitor during testing. It also required less number of displacement measuring devices. It has been used successfully for more than ten years. In Fig. 1 the cross-sectional parameters are illustrated and defined.

The tests were carried out in LERMA (Laboratory of Elasticity and Resistance of Materials), Universitat Politècnica de Catalunya, Barcelona, Spain.

Test specimens

Three different types of base plates shown in Fig. 2 were used. These types are typical for industrial cold-formed steel racks. Several identical samples of each type of base plate were tested at different axial load levels. The types sections tested are typical of the industrial applications in the United States.

Test results and their evaluation

The test results are shown in Fig.3. The vertical axis in these plots is the moment at the column base plate calculated from the forces, dimensions and displacements as follows:

$$M = (F_2 + F_1 \sin\beta)L + (F_1 \cos\beta)d_1$$

The horizontal axis is the rotation θ of the base plate in radians as defined in Fig. 1. Each plot shows the results of tests on a certain type specimens under different axial loads shown in the legend in lbs.

The tests were aimed at getting the moment rotation relationship, referred here as base stiffness as well as the ultimate value of the moment in the column at the base plate level. The notations regarding the test results are illustrated in Fig. 4 for two different tests. Mrd is the available flexural strength [factored resistance] calculated from flexural strength [resistance, ultimate load] by applying a safety factor or resistance factor. In the calculations presented here the resistance factor $\emptyset$ is taken as 0.5.

The following two different approaches were used to get Mrd from the flexural strength:

1. Approach 1: Flexural strength is taken as the maximum moment observed in the test.
2. Approach 2: Flexural strength is taken as the base moment at which the lateral load cannot be increased.

In Fig. 4 Type A base plate Test 5000-1 flexural strength based on maximum moment and the moment at maximum lateral load are the same whereas, in Test 15000-2 they are different as indicated. The differences between the results obtained using both approaches are due to the different behaviour of the samples in the final failure, which is influenced by various factors: the bending of the plate, the slippage of the anchorages, the buckling of the column, etc.

The specimen is considered failed when either one of the two following limits are reached:
- The lateral force decreases and descends to 0.
- The rotation of the column has reaches 0.12 rad.

Stiffness, K, is determined from the moment-rotation plot by drawing a secant to the curve from the origin to the moment Mrd. These values are designated as K1, K2, Mrd1 and Mrd2 depending on the approach used to define the ultimate moment.

For each test, Mrd and stiffness K are calculated and given in Table 1. All the calculated results are shown in Table 1. In this table the first column is the (axial load in lbs.) – (the test number).

To enable comparison, calculations are carried out according to EN 15512:2009 (which is the same as prEN 15512:2016). The parameters calculated according to the EN and prEN is designated as FEM.

The tabulated results are plotted in Figs. 5 through 7. Due to the availability of time and material, number of tests did not satisfy the requirement for multiple tests depending on the variation of the results. It would therefore be prudent to use lower bound to the test results for stiffness and strength. Equations for lower bound values for K (K1 Llim, and K2 Llim) and Mrd (Mrd Llim and Mrd Llim) are given and plotted in Figs. 5 through 7.

The values of K and Mrd obtained using Approach 1 appears to be reasonable in design because the base can still receive more moment beyond the Mrd computed from Approach 2, but the ultimate strength depends on the type of failure mechanism. The values of K obtained with Approach 2 are always higher, and the values of Mrd lower.

It is interesting to note that all the column base fixities are well below the value of 19,913 in-k/rad that can be obtained from the following equation given in the RMI Specification [1]:

$$\frac{M}{\theta} = \frac{bd^2E_c}{12}$$

Where b is the width of the column parallel to the flexural axis, d is the depth of the column perpendicular to the flexural axis, b is the width and E_c which is the modulus of elasticity of floor, assumed to be concrete and equal to
$E_{steel}/10$.

As mentioned above, in the calculations resistance factor ∅ was taken as 0.5. Comparing the results shown in Figs. 4, 5 and 6 with the results obtained according to prEN 15512:2016 (results designated FEM), it seems reasonable to increase the value of ∅ to 0.6. This would make a significant difference in Mrd but a much smaller difference in the value of K.

The use of the K and Mrd values in design would involve assuming reasonable values of K and Mrd at first and carrying out a frame analysis.

Depending on the outcome of the frame analysis, iterations may be necessary using the values of K and Mrd obtained from Figs. 4, 5 and 6.

The influence of the base fixity on the column base moment and the deflection at the first beam level of a multi-bay pallet cold-rolled steel rack can be seen in Fig. 8. This pallet rack was analyzed according to ANSI MH16.1: 2012 [1] for the parameters as follows:

- 5 levels of beams each 99 inches span and 60 in between levels
- Beams loaded uniformly with 3.56 k load
- Beam to column connection rotational fixity factor F= 750 k-in/radian
- Notional load factor = 1/240
- Column properties
    - $A_g = 0.936$ in^2 gross area of columns
    - $I_x = 1.27$ in^4 moments of inertia of columns about the axis of symmetry
    - $r_x = 1.16$ in radii of gyration of columns about the axis of symmetry
    - $S_e = 0.847$ in^3 section modulus of the columns
- Beam properties
    - $A_g = 0.780$ in^2 gross area of beams
    - $I_x = 1.70$ in^4 moment of inertia of the beams about the bending axis

It is seen in Fig. 8 that the change in M, moment at the base plate and the deflection at the fist beam level is not too sensitive to variations in the base fixity K above 4000 k-in/radian. It appears therefore that determination of an exact value of K is not too critical if K is larger than this value.

Summary and conclusions

Tests were conducted on column bases with three types of base plates under different levels of axial loads. The results show a wide variety of values for the ultimate moment and base fixity depending on the type of base plate and axial load. Therefore it would be prudent to assume lower bound values to the results in design.

Acknowledgement

The authors would like to acknowledge the support of the LERMA (Laboratory of Elasticity and Resistance of Materials), Universitat Politècnica de Catalunya, Barcelona and its capable staff as well as Rack

Manufacturers Institute and its Specification Advisory Committee, Dan Clapp, Chairman. Thanks are also due to Unarco Material Handling for the specimens used in the tests.

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5. Roure, F., Pastor, M. M. M. R. Somalo and Casafont, M, "New experimental method for determining the stiffness and strength of steel storage rack floor connections." 5th International Conference on Structural Engineering, Mechanics and Computation", 2-4 September 2013, Cape Town, South Africa

Test	K FEM	K 1	K FEM / K 1	Mrd FEM	Mrd 1	Mrd FEM / Mrd 1	K 2	K FEM/ K2	Mrd 2	Mrd FEM / Mrd 2
5000-1	5848.41	2634.28	2.22	19.22	28.34	0.68	2522.25	2.32	28.25	0.68
5000-2	6179.81	2362.00	2.62	19.15	29.09	0.66	2408.01	2.57	28.56	0.67
5000-3	4568.78	2365.03	1.93	19.12	24.78	0.77	2329.17	1.96	24.40	0.78
10000-1	6754.99	6579.08	1.03	25.95	25.03	1.04	6463.20	1.05	22.50	1.15
10000-2	6293.40	5580.17	1.13	25.57	27.78	0.92	6081.42	1.03	22.77	1.12
10000-3	6249.18	5100.82	1.23	26.06	28.02	0.93	6539.49	0.96	25.39	1.03
15000-1	6192.36	5854.51	1.06	32.48	32.22	1.01	6611.30	0.94	25.39	1.28
15000-2	6756.52	6736.32	1.00	31.98	28.67	1.12	7389.83	0.91	24.63	1.30
15000-3	6972.00	7157.16	0.97	32.42	31.65	1.02	6429.23	1.08	21.43	1.51

Type A Base plate

Test	K FEM	K 1	K FEM / K 1	Mrd FEM	Mrd 1	Mrd FEM / Mrd 1	K 2	K FEM/ K2	Mrd 2	Mrd FEM / Mrd 2
5000-1	897.63	808.30	1.11	14.15	13.52	1.05	925.24	0.97	10.93	1.30
5000-2	2540.30	2228.57	1.14	14.14	14.26	0.99	2576.08	0.99	12.10	1.17
5000-3	2056.10	1724.00	1.19	14.13	14.99	0.94	1960.50	1.05	13.06	1.08
7500	3043.05	2519.30	1.21	17.49	17.95	0.97	3481.14	0.87	14.15	1.24
10000-1	2597.73	2173.45	1.20	19.89	20.79	0.96	2795.90	0.93	15.72	1.27
10000-2	2204.45	1963.37	1.12	19.62	19.35	1.01	2542.46	0.87	14.76	1.33
12500-1	2347.22	2125.98	1.10	21.04	20.08	1.05	2670.28	0.88	15.66	1.34
12500-2	3170.58	2831.22	1.12	20.80	20.28	1.03	4999.64	0.63	14.30	1.45
15000-1	2835.87	2750.43	1.03	23.13	21.55	1.07	3071.87	0.92	18.87	1.23
15000-1	2683.30	2644.91	1.01	23.27	21.54	1.08	3938.83	0.68	14.99	1.55
20000-1	4756.34	4670.02	1.02	24.70	22.68	1.09	6426.20	0.74	15.35	1.61
20000-2	3352.63	3625.77	0.92	24.24	21.38	1.13	6466.08	0.52	13.40	1.81

Type B Base plate

Test	K FEM	K 1	K FEM / K 1	Mrd FEM	Mrd 1	Mrd FEM / Mrd 1	K 2	K FEM/ K2	Mrd 2	Mrd FEM / Mrd 2
5000-1	1089.76	1074.54	1.01	4.44	3.58	1.24	1140.66	0.96	2.68	1.66
5000-2	1564.03	1468.96	1.06	4.54	4.13	1.10	1589.50	0.98	3.01	1.51
7500-1	3172.75	3949.80	0.80	8.53	6.02	1.42	4090.34	0.78	5.14	1.66
10000-1	3885.03	4370.92	0.89	10.20	7.16	1.42	4728.46	0.82	6.09	1.68
10000-2	4792.14	5248.22	0.91	10.02	8.02	1.25	5395.87	0.89	6.39	1.57
12500-1	4457.69	4262.73	1.05	12.22	10.36	1.18	4192.05	1.06	8.58	1.42
15000-1	4345.86	4877.32	0.89	17.66	11.65	1.52	5663.22	0.77	8.58	2.06
15000-1	5393.41	5235.37	1.03	17.67	12.94	1.37	5656.35	0.95	11.94	1.48
20000-1	4672.11	5178.97	0.90	20.20	14.58	1.39	5435.07	0.86	12.43	1.63

Type C Base plate

Table 1 Stiffness and design moments base on test results

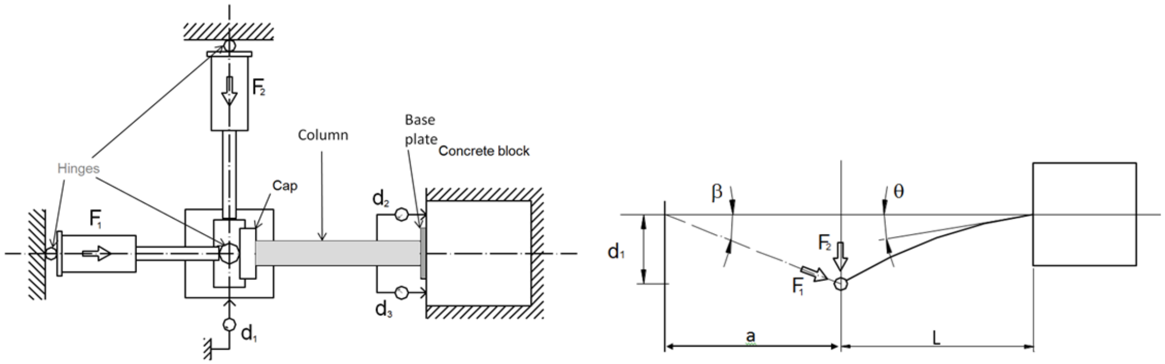
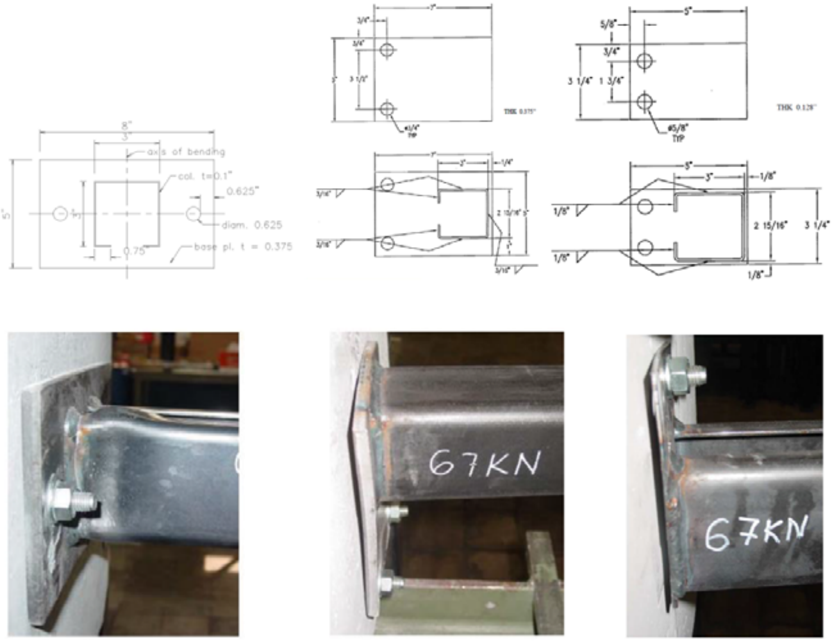


Fig. 1 Test setup and measurements

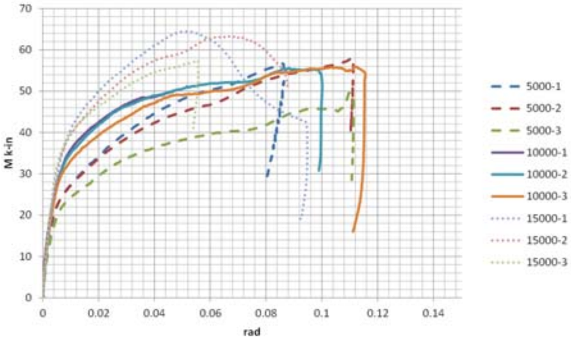
d_1 to d_3	displacement measuring devices
d_{23}	dimension between measuring devices d_2 and d_3
F_1 & F_2	forces applied by jacks
θ_b	rotation of the base plate.
β	angle between axial force and the initial alignment = arc tan (δ_1/a)
δ_1	displacement of the top of the upright measured by d_1

Fig. 2 Test setup

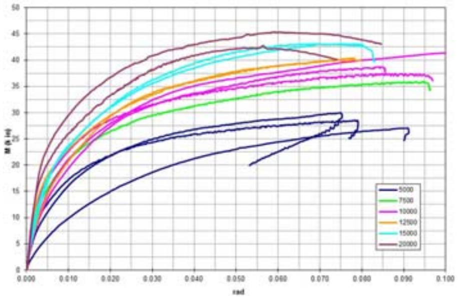


Type A Type B Type C

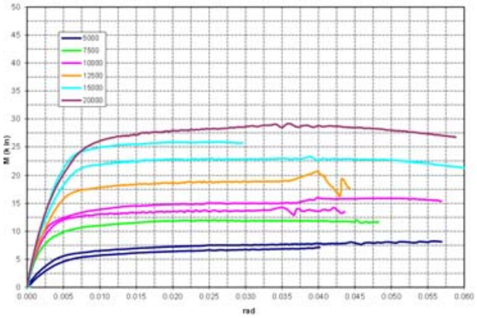
Fig. 2 Test specimen types



Type A Specimens

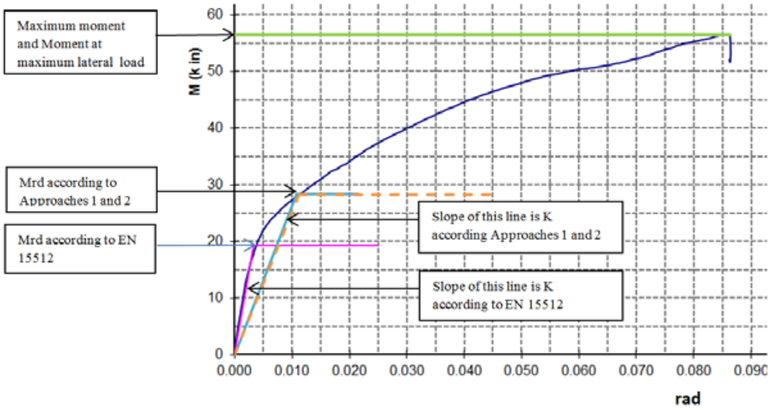


Type B Specimens

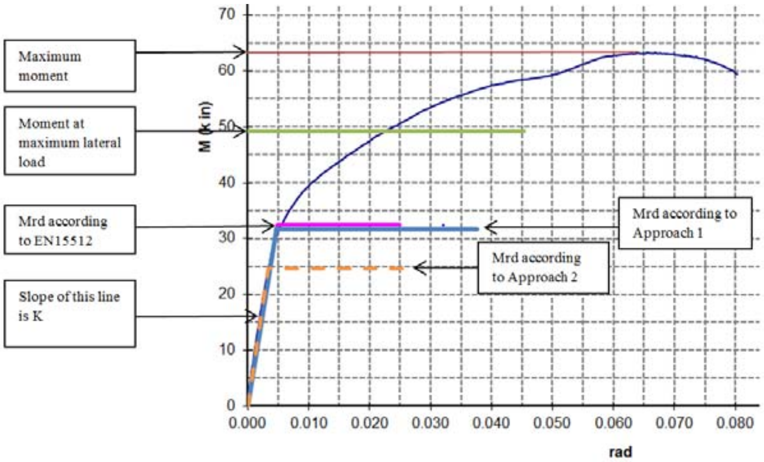


Type C Specimens

Fig. 3 Test results

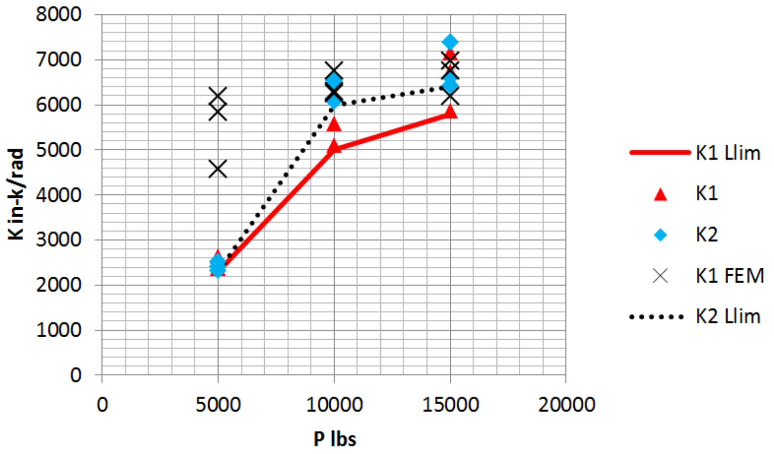


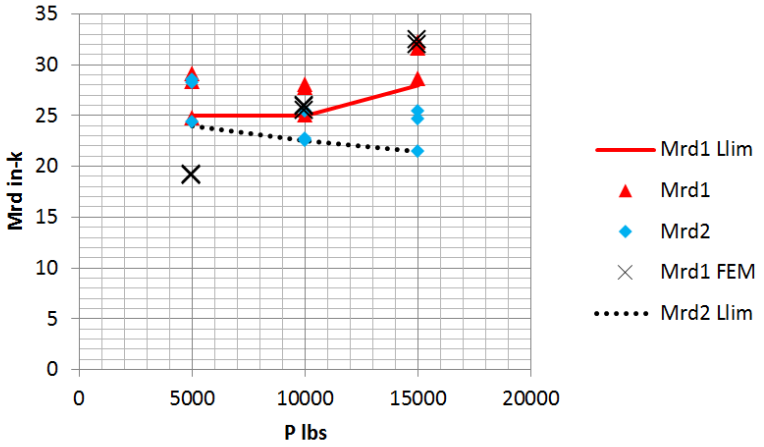
Type A Test 5000-1



Type A Test 15000-2

Fig. 4 Mrd and K from test results





$K1 = 0.54P - 400 \; for \; 5000 \leq P < 10000$

$K1 = 0.16P + 3400 \; for \; 15000 \geq P \geq 10000$

$K2 = 0.74P - 1400 \; for \; 5000 \leq P < 10000$

$K2 = 0.16P + 4400 \; for \; 15000 \geq P \geq 10000$

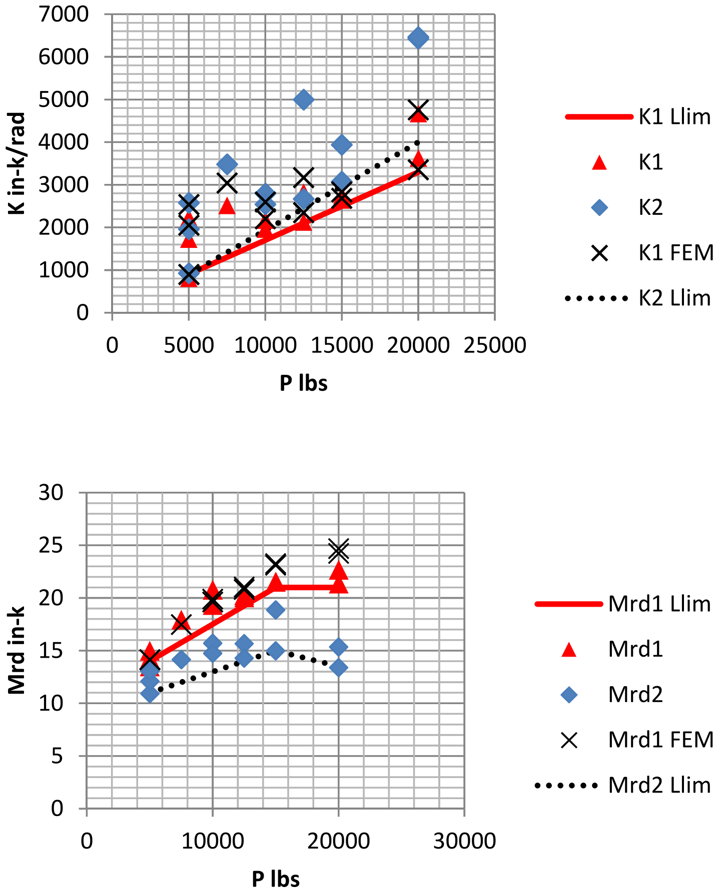
$Mrd1 = 25 \; for \; 5000 \leq P < 10000$

$Mrd1 = 0.0006P + 18 \; for \; 15000 \geq P \geq 10000$

$Mrd2 = 0.0003 + 21 \; for \; 5000 \leq P < 10000$

$Mrd2 = 0.0002P + 24.5 \; for \; 15000 \geq P \geq 10000$

Fig. 5 Results for tests on Base plate Type A



$K1 = 0.16P + 100\ for\ 5000 \leq P < 20000$

$K2 = 0.207P - 133.33\ for\ 5000 \leq P < 20000$

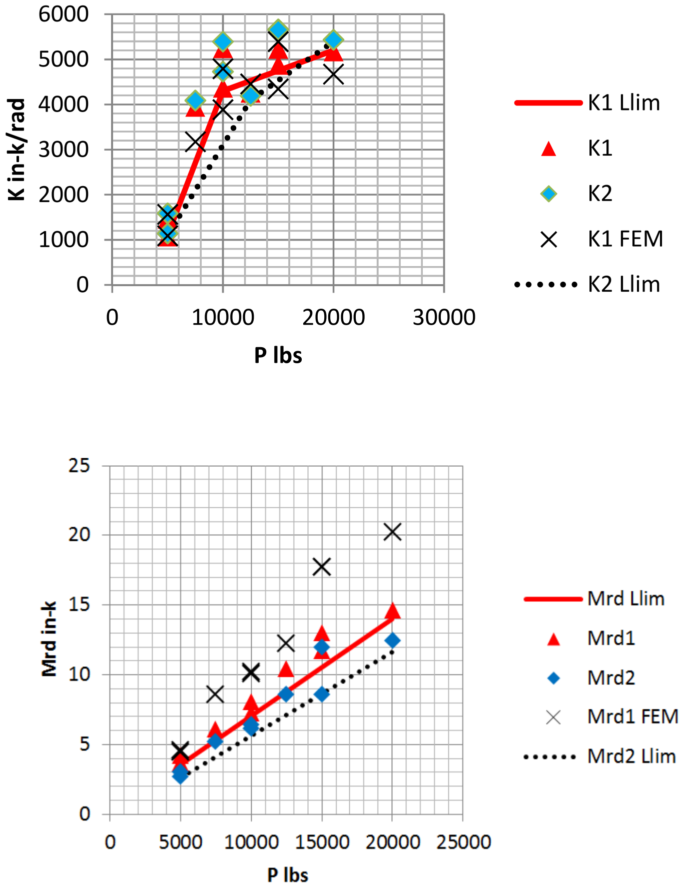
$Mrd1 = 0.0007 + 10.5\ for\ 5000 \leq P < 15000$

$Mrd1 = 21\ for\ 20000 \geq P \geq 20000$

$Mrd2 = 0.0007 + 10.5\ for\ 5000 \leq P < 10000$

$Mrd2 = 0.0003P + 19.5\ for\ 20000 \geq P \geq 10000$

Fig. 6 Results for tests on Base plate Type B



$$K1 = 0.54P - 400 \ for \ 5000 \le P < 10000$$

$$K1 = 0.16P + 3400 \ for \ 15000 \ge P \ge 10000$$

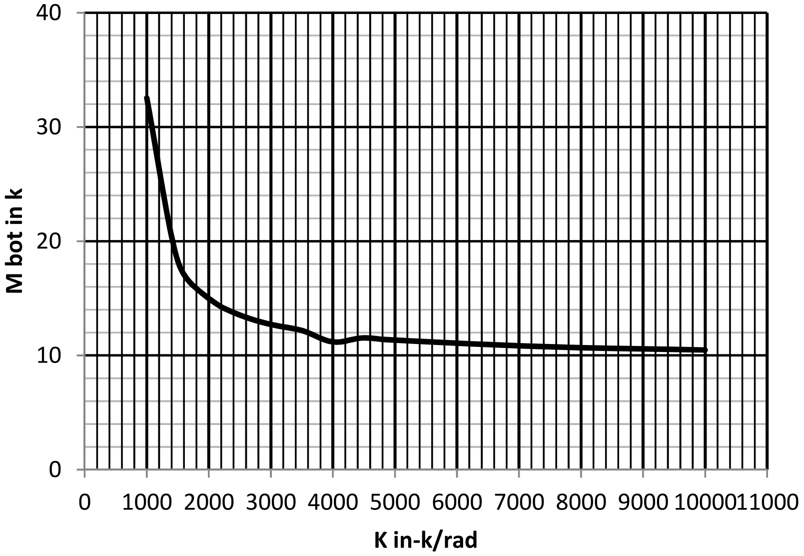
$$K2 = 0.74P - 1400 \ for \ 5000 \le P < 10000$$

$$K2 = 0.16P + 4400 \ for \ 20000 \ge P \ge 10000$$

$$Mrd1 = 0.0006933P + 0.133 \ for \ 20000 \ge P \ge 5000$$

$$Mrd2 = 0.00076P + 1.2 \ for \ 20000 \ge P \ge 5000$$

Fig. 7 Results for tests on Base plate Type C



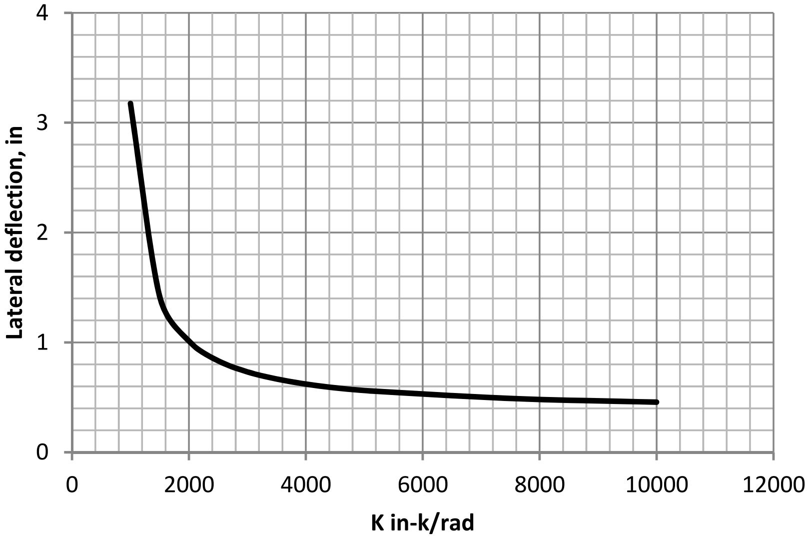


Fig. 8 Numeric Example