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POST-YIELD DEFLECTIONS OF ELASTIC-PLASTIC BEAMS UNDER UNIFORMLY INCREASING LOADS

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Experiments on single span and double span beams beyond the elastic range are reported on in the case when the applied load increases in proportion. The test results are examined in accordance with a deflection analysis based on different approaches. The comparison made allows to state that the finite spread of plastic zones should be accounted for when calculating deflections in the post-elastic range.

1. Introduction

Available methods of plastic analysis allow easily to estimate the load-carrying capacity of an elastic-plastic beam [4, 11, 12, 19, 20 and 21]. The rigid-plastic model of material response is found experimentally to yield safe values of the collapse for stiff metal structures. The plastic methods are nowadays widely admitted by the codes of structural design [17, 18].

The collapse load analysis constitutes, however, only one part of the structural design of elastic plastic structures, the other being the deflection evaluation. When a structure enters the plastic range, then under continued loading the yielding zones spread over the structure and its stiffness diminishes. The most widely used method of deflection evaluation assumes that the yielding zones are localized to plastic hinges whereas the stiffness remains unchanged elsewhere. Such an approach leads necessarily to underestimation of deflections except in the case of ideal I–section beams and frames [4, 13, 1]. Moreover, for structures designed according to the plastic methods an evaluation of deflections is required at service loads when the structure is only partially plastic and does not transform yet into a mechanism. Methods for computing deflections in such situations have been proposed in [2, 3, 8].

Further questions in elastic-plastic design concern the overall post-yield behaviour when yielding zones develop in a structure, possibly yield hignes form and particular plastic zones consequentively enter the hardening range. Moreover, the behaviour of actual structures at repeated loads constitute an important factor in structural design [6, 7, 14].

Application of plastic methods in design requires appropriate experimental research to validate theoretical predictions furnished by various analytical methods for evaluation of the deformability. Available experiments were not sufficient to evaluate the developed methods of displacement estimation and to conclusions suitable for design practice.

A series of experiments has been undertaken to study the behaviour of continuous beams beyond the elastic range. The limit analysis, shakedown and post-yield behaviour of metal beams of a rectangular cross-section have been studied.

The present note relates to the first part of the experimental program intended to furnish design data in view of the admission of the plastic design methods by the Polish Building Code [17] and by the European Recommendations [18]. Experiments on single span and double span beams are reported on in the case when the applied loads increase in proportion. The program of experiments and characteristics of the test beams are given in Sects. 2 and 3, respectively. Section 4 deals with the test stand and describes the measurements. Experimental data regarding deflections of a single span, simply supported beam are presented in Sect. 5 whereas the analogous results for a two-span beam under two types of loading are given in the next section. The obtained data are compared with analytical predictions in Sect. 6. The discussions and conclusions are given in the last section.

The note presents the obtained experimental material quite extensively in order to furnish data not only for comparisons with existing theories regarding deformability of elastic-plastic beams but also to facilitate to some extent further analitical studies concerning the post yield behaviour, specifically the effect of material hardening and large displacements on the load carrying capacity of metal structures. Experiments on shakedown are discussed elsewhere [5, 9].

2. TEST PROGRAM

The test program concerns deformability and load carrying capacity of beams under continuously increasing loading. The beams are subjected to concentrated forces at the mid-span. The following types of simply supported structures are considered: a) single span beams under single load, b) two-span beams loaded at one span, c) two-span beams loaded at both spans.

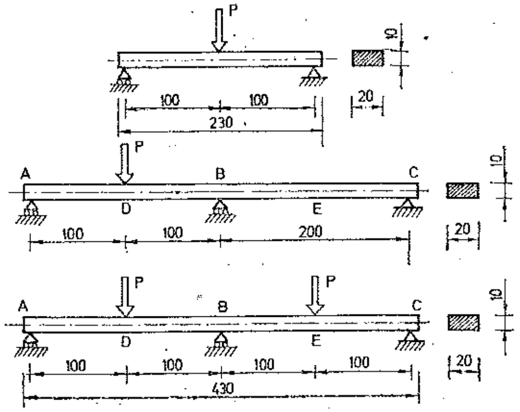

FIG. 1. Loading arrangements.

In each case five specimens are tested. The loading and testing arrangements are shown in Fig. 1. The models have a rectangular cross-section, whereas the loads are continuously increasing by small steps until the deflections under the loads are of the order of the beam depth. The deflections are recorded at midspans and at supports. This allows to trace the load-deflection curve fairly beyound the collapse load in order to account for large deformations and displacements at hardening.

3. Specimens

The tested beams of a cross-section 10–20 mm were cut from a metal bar in the direction of rolling to yield 5 elements of a length 230 mm and 10 elements of length 430 mm. The surfaces were polished and the cross-sections deviated at most ±0.05 mm from the required dimensions.

The mild steel St–35 was used as this type of material is widely employed when constructing steel structures. The material composition contained C–1.70‰, Mn–0.67‰, Si–0.26‰ P–0.025‰ and S–0.021‰.

Material testing with regard to its mechanical properties was made on bars 10–20 mm of 200 mm reference length as required by the respective Polish Standards for evaluating such properties under static loading conditions. All beams and material specimens were annealed during one hour at a temperature 650°C and then cooled to the ambient temperature for about 30 hours. A typical stress-strain curve is shown in Fig. 2. From five specimens the average values of the mechanical properties involved in further analysis were: the Young modulus $E=210680$ MPa, the yield point $\sigma_0=315.29$ MPa, the elastic deformation at the yield point $\varepsilon_E=1498\cdot 10^{-6}$, the plastic platform $\varepsilon_p=2.92\varepsilon_E$ and the tensile strength $R_m=446.65$ MPa. In Fig. 2 the average yield stress is indicated as well as the tensile strength. Standard deviations of the observed quantities with respect to the mean values were: 1.8% for the yield strength, 4% for the elastic strain and 6.3% for the plastic strain at the beginning of hardening.

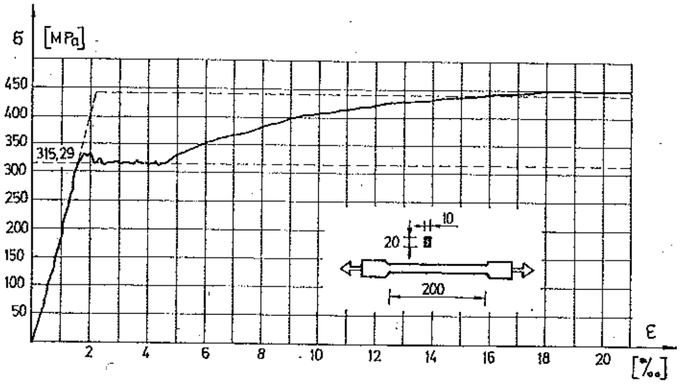

FIG. 2. Stress-strain diagram of the material employed.

The full plastic moment of the beam is Mo=15764 Ncm whereas the bending moment associated with the true stress strain diagram when the outer fibres enter into the hardening range is M_H=15421 Ncm which is equal M_H=0.978 Mo. The moment corresponding to the maximum strength obtained in the most strained fibre is M_R=16696 Ncm which is equal M=1.06 Mo.

4. TEST STAND

The test stand and the arrangements for loading as well as for displacement evaluation are shown in Fig. 3. Careful arrangements were made in order: a) to assure simple supports of beams allowing for free horizontal movements, b) to get a fairly pointwise and not eccentric transmission of loading, c) to allow for a slow loading and unloading, d) to assure appropriate measuring of displacements at the selected points.

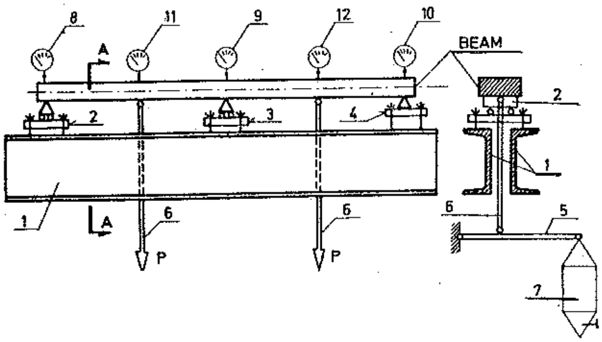

FIG. 3. Test stand.

The test stand shown in Fig. 3 consists of a stiff supporting frame *1* and two hinges *2* and *3* allowing the tested beams to rotate and to support horizontal displacements. Moreover, these supports provide for the possibility of vertical adjustment. There is an immovable support *4* and a loading device consisting of two levers *5*, a tendon *6* and two loading containers *7*. Details are given in [5].

The loading increases when tokens are put in the container. The load increase was variable but at maximum 117 N, what constitutes about 0.037 of the computed collapse load. In all the cases tested vertical displacements are measured by dial gauges 11 and 12 at the same instant when displacements of the supports are recorded by the gauges 8, 9 and 10. Reading of the dial gauges allowing for the accuracy of 0.01 mm are made 10 minutes after the loading is increased. The displacements of supports are taken into account when computing actual displacement of the beam.

The test stand and a beam under loading are shown in Fig. 4.

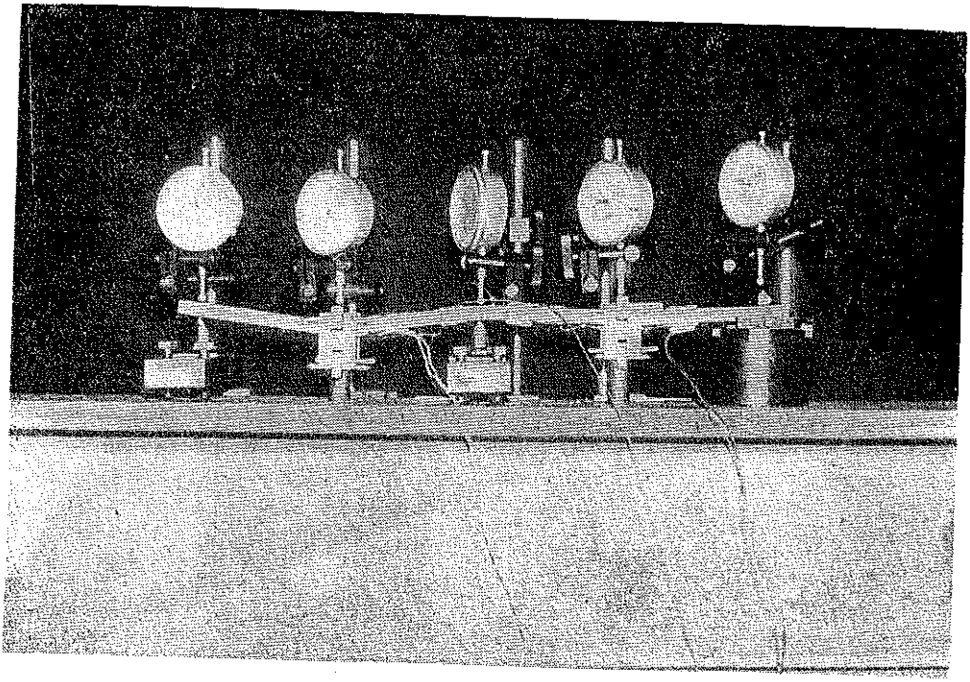

FIG. 4. Teste arrangement.

5. SINGLE SPAN BEAMS

Five single span beams have been tested according to the loading scheme shown in Fig. 1a. The main purpose of such a test was twofold. In the first place, it was intended to obtain experimental data for the case when elastic-plastic solutions regarding displacements are known [12, 15]. The second purpose was to check the stand and the measuring procedure in view of further tests concerning two span beams under increasing load as well as under repeated loading under shakedown conditions and beyond.

The test results are given in Table 1. Purposely, the loading was continued up to advanced displacements in order to get data for large deflections and therefore concerning the behaviour beyond the static collapse load. The experimental scatter of data is larger advanced loading varying from 4% to 24% of the average deflection.

In Fig. 5 the average values are compared as regards the load-displacement relation for the point of loading. For comparison the solution concerning an elastic-perfectly plastic beam of rectangular and ideal sandwich cross-section are given. The collapse load is in this case $P_L=4$ Mo$/L=3149$ N.

It can be noticed that for loads below the limit load experimental data follow fairly close the theoretical values. At the limit load P_L for all the beams a marked increase in deflections was observed under loading tending to the yield point value, whereas beyond the collapse load the influence of hardening can be distinguished.

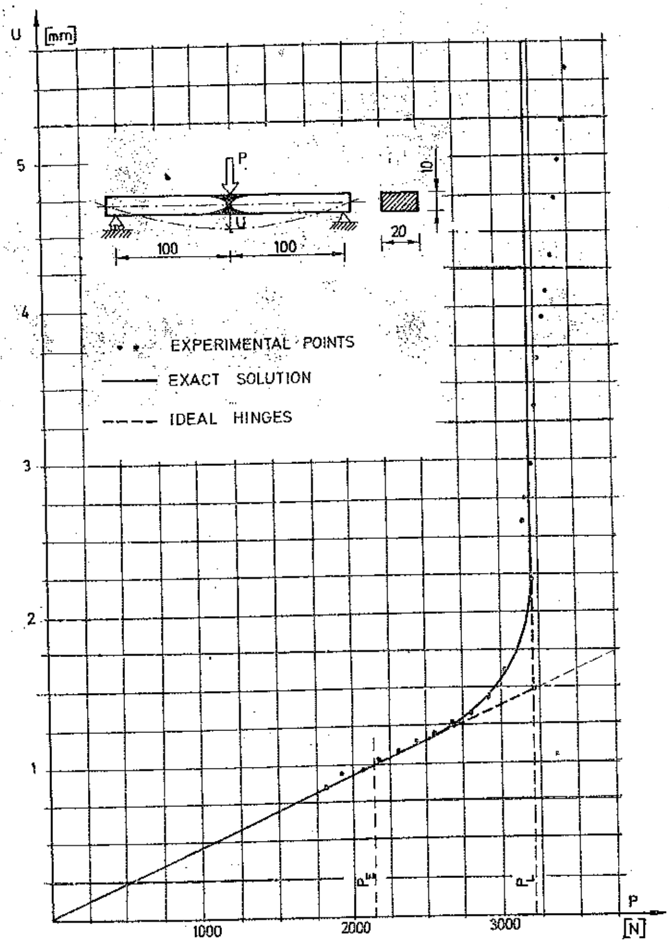

FIG. 5. Load deflection relations.

6. DOUBLE SPAN BEAMS

Continuous beams were tested at monotonous loading on models of 200 mm spans for two cases of loading conditions shown in Fig. 1b, c. In each case five specimens were tested at the same loading pace.

For the case of two span beams loaded at the center of one span the test results are given in Table 2. The loading was continued far beyond the limit load of a perfectly plastic structure. In Fig. 6 the results are plotted and the mean value deflections traced. For the sake of comparison and a discussion later, the theoretical values of the elastic limit load P_E, the load associated with the first plastic hinge formation P_I and the yield point load P_L are indicated:

$$P_E = \frac{128}{39}\,\frac{Mo}{L} = 2580\,N, \quad P_I = \frac{64}{13}\,\frac{Mo}{L} = 3875\,N, \quad P_L = \frac{6Mo}{L} = 4728\,\mathrm{N}$$

Table 1. Experimental data for single supported beams

Load N	Displacemens [mm]					Mean value	Standard deviation
	1	2	3	4	5		
1	2	3	4	5	6	7	8
1791	0.87	0.91	0.83	0.81	0.85	0.85	0.034
1911	0.92	0.96	0.89	0.86	0.90	0.91	0.037
2030	0.97	1.01	0.95	0.91	0.96	0.96	0.036
2149	1.04	1.07	1.01	0.96	1.01	1.02	0.041
2268	1.10	1.15	1.07	1.02	1.07	1.08	0.048
2387	1.16	1.21	1.12	1.10	1.14	1.15	0.042
2507	1.22	1.26	1.19	1.14	1.20	1.20	0.044
2626	1.27	1.33	1.23	1.21	1.25	1.26	0.046
2746	1.36	1.41	1.30	1.26	1.30	1.33	0.059
2854	1.52	1.55	1.38	1.35	1.37	1.43	0.093
2984	1.77	1.84	1.57	1.44	1.44	1.61	0.185
3104	3.86	3.75	2.12	1.62	1.60	2.59	1.129
3123	4.22	3.90	2.20	1.73	1.65	2.74	1.228
3162	4.35	4.25	2.72	1.83	1.69	2.97	1.279
3193	4.62	4.45	4.02	1.99	1.74	3.36	1.389
3222	4.89	4.75	4.12	2.76	1.82	3.67	1.333
3253	5.07	5.18	4.49	3.06	1.91	3.94	1.415
3282	5.33	5.25	4.62	3.31	2.01	4.10	1.423
3312	5.47	5.55	4.87	3.66	2.17	4.34	1.431
3342	5.59	5.94	4.95	3.92	3.17	4.71	1.556
3372	5.86	6.11	5.20	4.12	3.57	4.97	1.099
3402	6.16	6.44	5.23	4.40	3.93	5.23	1.085
3431	6.37	6.84	6.15	4.45	4.07	5.58	1.234
3461	6.88	7.13	6.21	4.61	4.35	5.84	1.286
3491	7.30	7.31	6.32	4.96	4.65	6.11	1.260
3528	7.47	7.54	6.73	5.06	4.82	6.32	1.305
3551	8.15	7.73	6.87	5.31	5.01	6.61	1.409
3580	8.52	8.08	7.25	5.71	5.25	6.96	1.437
3610	8.79	8.43	7.55	5.91	5.52	7.24	1.470
3639	8.90	9.32	8.15	6.37	5.75	7.70	1.568
3669	9.67	9.62	8.35	6.51	6.00	8.03	1.714
3699	10.22	10.02	8.95	6.86	6.26	8.46	1.815
3728	10.73	11.32	9.20	7.26	6.47	9.00	2.112

The second case of loading of continuous beams concerned the equal loads in both spans. The recorded results for the same loading steps as in the preceding case are given in Table 3. The average values are used in Fig. 7 to trace the experimental load-displacement curve. For information, the elastic limit P_E, the loads associated with the first plastic hinge formation P_I and the collapse load P_L are marked in the figure as well as the scatter of the data indicated.

$$P_E=\frac{128}{30}\,\frac{\mathrm{Mo}}{L}=2802\ \mathrm{N},\quad P_I=\frac{64}{12}\,\frac{\mathrm{Mo}}{L}=4198\ \mathrm{N},\quad P_L=\frac{6\mathrm{Mo}}{L}=4728\ \mathrm{N}.$$

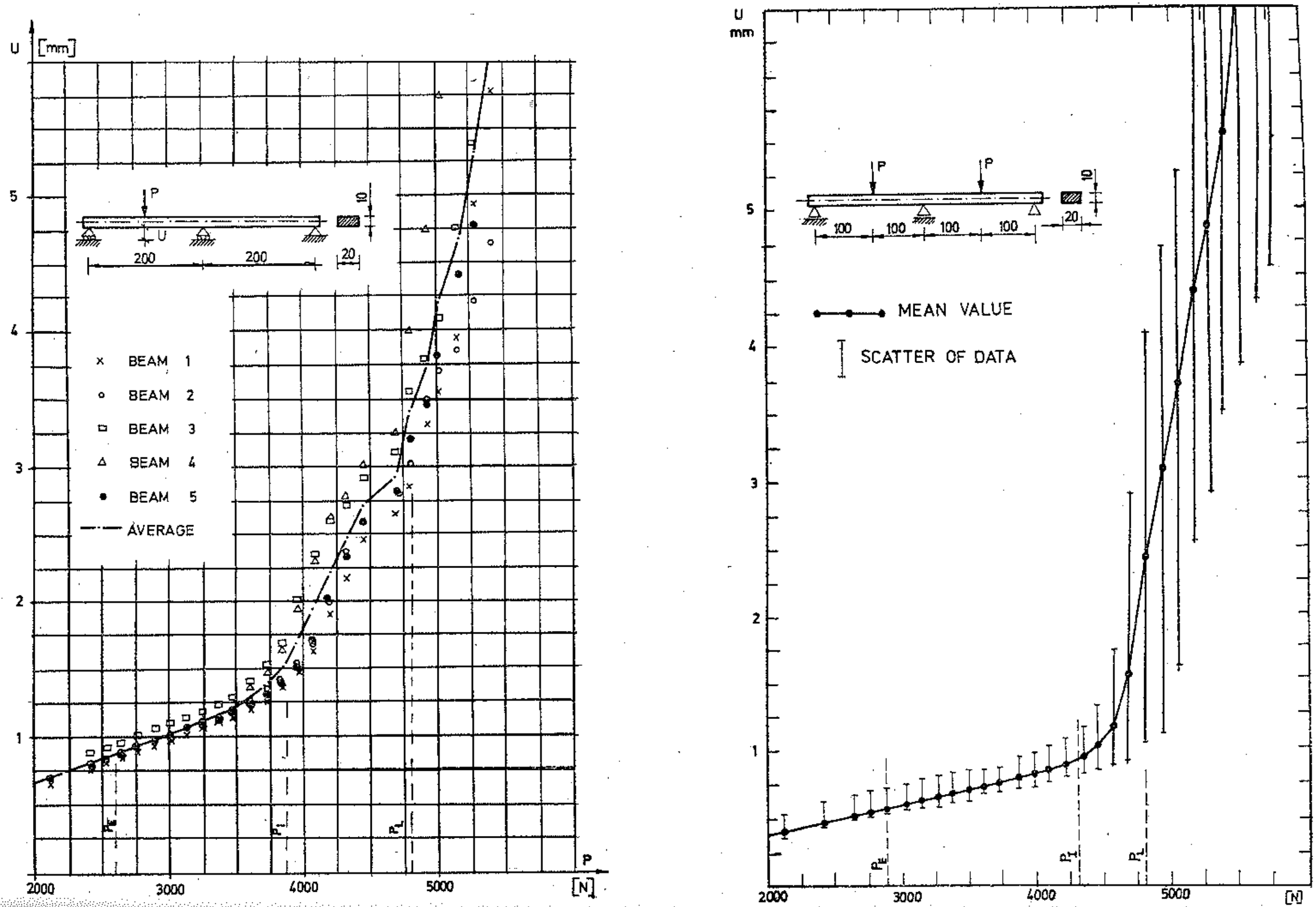

Fig. 7. Scatter of results.

Table 2. Experimental data for double span beams with single load

Load N	Displacements [mm]$\times 10^{-2}$					Mean value	Stand. dev.
	1	2	3	4	5		
1	2	3	4	5	6	7	8
2070	65	70	79	68	69	70.4	5.2
2364	77	81	90	81	78	81.4	5.1
2482	81	83	93	85	82	84.8	4.8
2600	85	87	97	89	87	89.0	4.7
2717	89	92	101	93	91	93.2	4.6
2835	93	97	106	97	97	98.0	4.8
2953	98	100	110	102	101	102.2	4.6
3071	102	106	113	107	107	107.0	3.9
3188	106	110	118	110	109	110.6	4.5
3306	111	114	123	116	113	113.4	4.6
3424	115	119	130	122	117	120.6	5.9
3541	120	129	140	136	124	129.8	8.3
3659	126	136	153	146	130	138.2	11.2
3777	138	142	169	163	140	150.4	14.5
3895	147	154	199	193	152	169.0	24.9
4012	165	170	235	230	171	194.2	35.1
4130	190	200	256	257	202	221.0	32.7
4248	216	236	272	279	233	247.2	27.1
4365	245	260	291	301	258	271.0	23.8
4483	263	283	311	325	282	292.8	24.8
4601	283	303	336	355	392	319.2	32.3
4719	302	322	357	399	322	340.4	38.3
4836	331	349	380	418	346	376.8	59.3
4954	355	371	410	577	381	418.8	90.7
5072	395	396	476	647	438	468.4	106.1
5190	494	423	539	725	480	532.2	115.5
5307	578	465	616	814	609	616.4	126.0
5425	678	568	678	894	678	699.2	118.9
5543	778	657	757	963	748	780.6	112.0
5660	878	767	832	1032	817	865.2	101.3

The results are compared to the relationship following from the theory of deflection evaluated assuming ideal plastic hinges.

It is worthwhile to point out that two loading schemes give the same collapse load but have distinct elastic limit loads. Comparison of these two sets of experiments allows to estimate the spread of plastic zones influence on the magnitude of deflections.

In Fig. 8 the tested beams are shown after unloading. The mechanisms of plastic collapse are clearly visible. The single span beams were loaded up to $P=1.18\ P_L$ whereas the continuous ones to $P=1.20\ P_L$.

Table 3. Experimental data for double span beams with load in both spans

Load N	Displacements W_A [mm] 10^{-2}							Displacements W_B [mm] 10^{-2}							Mean value	Stand. dev.
	1	2	3	4	5	Mean	St. dev.	1	2	3	4	5	Mean	St. dev.		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2070	43	45	55	39	52	46.8	6.6	44	45	40	37	43	41.8	3.3	44.3	5.6
2364	50	50	63	46	60	53.8	7.3	54	54	48	45	49	50.0	3.9	51.9	5.9
2600	56	57	67	52	64	59.2	6.1	58	58	54	51	53	54.8	3.1	57.0	5.1
2717	58	59	71	56	66	62.0	6.3	60	62	57	52	57	57.6	3.8	59.8	5.4
2835	62	64	73	59	70	65.6	5.8	63	64	60	53	59	59.8	4.3	62.7	5.7
2953	65	65	77	60	73	68.0	6.9	66	68	61	58	61	62.8	4.1	65.4	6.0
3071	68	67	79	65	75	70.8	5.9	68	69	64	59	64	64.8	4.0	67.8	5.7
3188	70	69	81	69	77	73.2	5.5	70	73	66	60	66	67.0	4.9	70.1	5.9
3306	73	72	84	72	79	76.0	5.3	73	75	69	62	67	69.2	5.1	72.6	6.1
3424	76	75	86	75	83	79.0	5.1	75	78	71	64	71	71.8	5.3	75.1	6.1
3541	77	80	91	76	86	82.0	6.4	82	79	74	70	76	76.2	4.6	79.1	6.1
3659	79	82	94	80	88	84.6	6.3	85	83	76	71	78	78.6	5.6	81.6	6.5
3777	81	85	97	82	91	87.2	6.7	86	86	79	73	81	81.0	5.4	84.1	6.6
3895	86	88	99	87	84	90.8	5.5	88	88	81	74	82	82.6	5.8	86.7	6.9
4012	89	90	103	91	98	94.2	6.1	90	92	85	77	84	85.6	5.9	89.9	7.2
4130	93	95	110	96	102	99.2	6.9	95	101	90	83	86	91.0	7.2	95.1	7.9
4248	97	102	117	105	106	105.4	7.4	101	106	93	85	89	94.8	8.6	100.1	9.4
4365	104	106	127	114	110	112.2	9.1	109	117	99	87	92	100.8	12.3	106.5	11.8
4483	114	115	174	139	115	131.4	26.0	122	138	110	91	94	111.0	19.6	121.2	24.3
4601	130	145	291	182	123	174.2	69.1	145	262	126	96	100	145.8	68.0	160.0	66.4
4719	266	235	363	410	137	282.2	107.7	277	354	223	124	107	217.0	103.9	249.6	105.5
4836	353	276	445	473	162	341.8	127.1	362	435	270	231	116	282.8	122.6	312.3	121.8
4954	419	345	496	514	321	419.0	86.7	423	524	313	248	163	334.2	142.4	376.6	119.8
5072	484	401	567	592	418	491.2	84.5	483	602	354	272	257	393.6	147.0	442.4	124.2
5190	490	450	640	848	477	579.4	167.6	527	691	403	291	306	443.6	167.4	491.7	138.3
5307	514	523	727	692	546	600.4	101.0	591	783	453	426	356	521.8	169.1	561.1	137.7
5425	562	583	804	773	600	664.4	114.6	691	860	508	495	387	588.2	187.1	626.3	151.7
5543	610	533	865	861	685	730.8	123.7	783	944	569	564	437	659.4	201.9	695.1	162.3
5660	660	713	940	927	749	797.8	127.9	979	1047	642	622	461	750.2	251.1	774.0	189.6

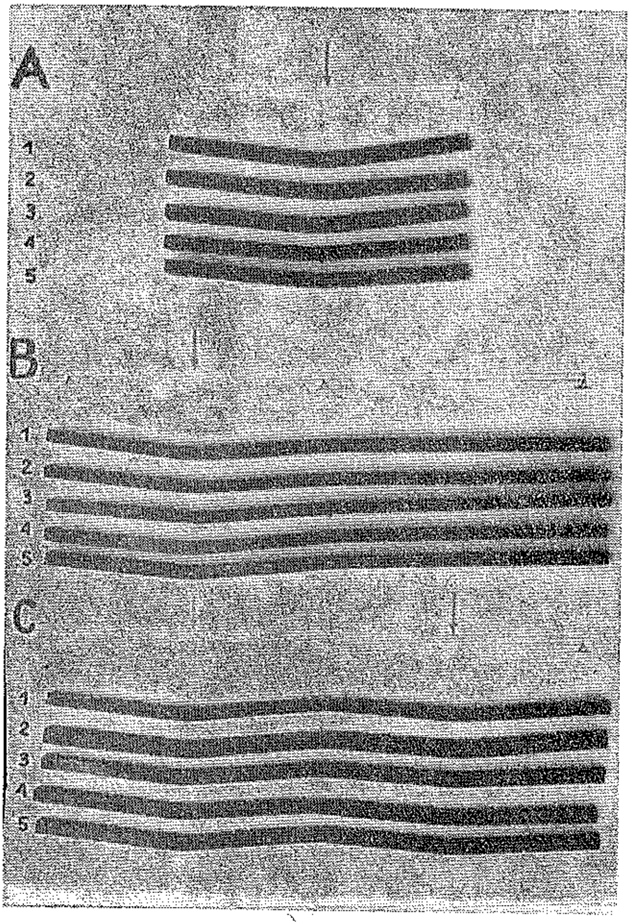

FIG. 8. Beams after testing.

7. COMPARISONS

Evaluation of deflections of beams at elastic-plastic deformations is fairly complicated and, although straightforward, does not possess the simplicity of the collapse load calculations amploying the static or the kinematic theorem of the limit analysis. Various approximate methods exist and they mostly differ by the manner they account for the spread and extent of plastic zones when the load increases beyond the elastic limit. Before we pass to some comparisons, let us first consider the influence of plastic zones on the stiffness of a structure, thus on its deflections.

In Fig. 9 the deflections at the loading points are referred to the elastic deflections and traced versus the dimensionless load $p = P/P_L$. Each of the loading cases is associated with a different stiffness variation, hence the load-deflection curves are different. These experimental values allow to draw some conclusions regarding the magnitude of deflections beyond the yield point load for work-hardening structures. At the same collapse load in the cases b) and c) the deflections are markedy different.

Let us now compare the results of experiments with the deflections given by the method of ideal plastic hinges for the two-span beam studied. The results are

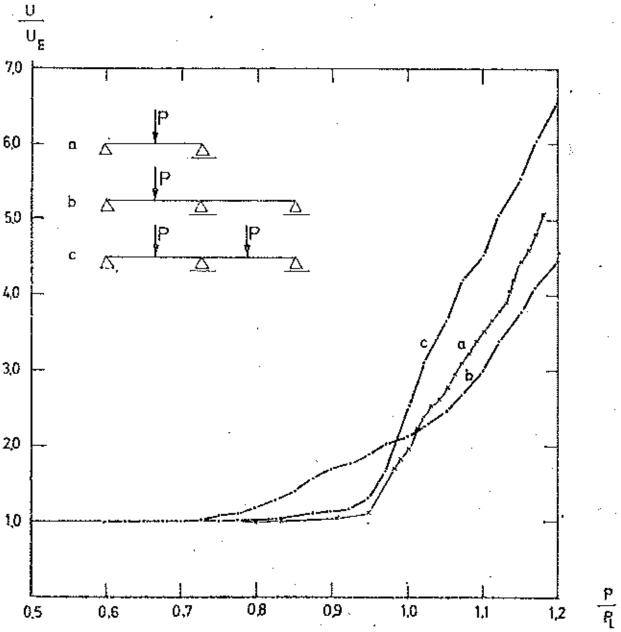

FIG. 9. Load deflection relations.

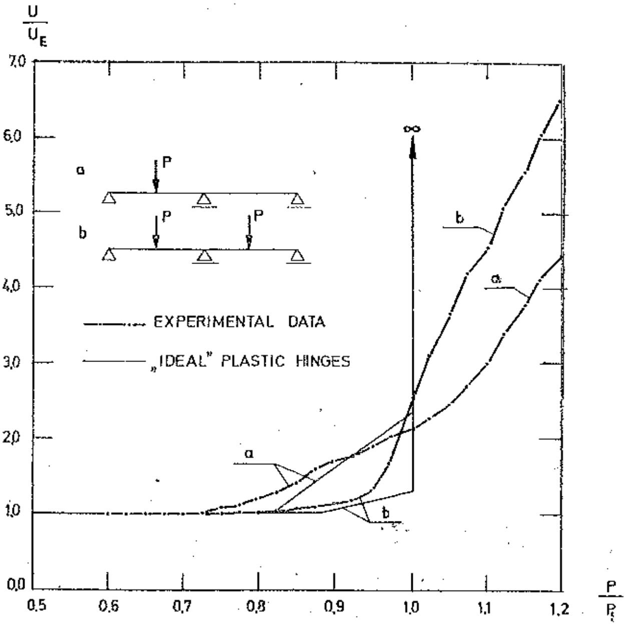

FIG. 10. Actual and theoretical deflections according to classical method.

given in Fig. 10. It is seen that the classical method of the deflections evaluation underestimates the actual deformability of a structure. It is thus necessary to account for a finite spread of plastic zones when calculating the deflections under loading crossing the elastic limit load.

Among the existing methods concerning the deflection estimation, we consider two accounting for the finite spread of plastic zones. The first one developed in [1] consists in replacing the beam stiffness reduction due to yielding by an appropriately determined step-wise rigidity change and to compute displacement of the obtained structure employing the usual procedure regarding elastic beams. The method is approximate and gives only deflections at the collapse load since the stiffness variation is not here continuously increasing with the load increase.

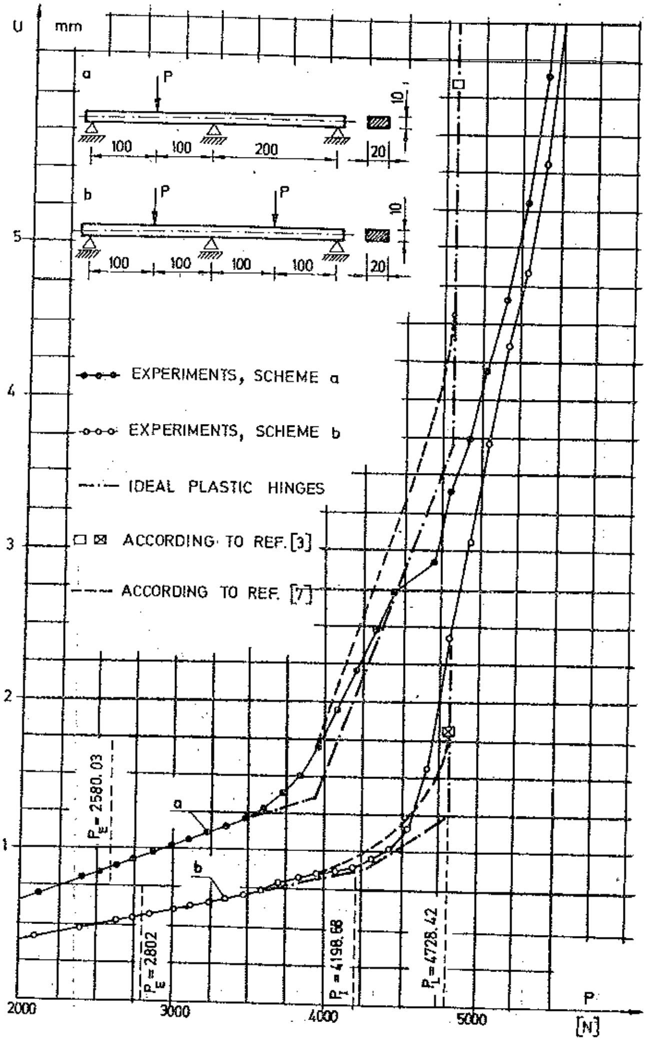

FIG. 11. Deflections versus loading.

The second approach as developed in [3] and [8] accounts for the finite spread of the plastic zones introducing an additional term in the ideal hinge method. The additional term is appropriately related to the shape of the plastic zone which in turn depends on the loading applied to a beam.

In Fig. 11 experimental results are compared to the deflection estimation methods referred to. It is seen from Fig. 10 that for the loads below the yield point load the experimental results and the theoretical predictions according to approximate methods are fairly close. The discussed methods are in better agreement with the experimental results than the idealized hinge method assuming localized stiffness changes as given by the broken lines in Fig. 11.

8. Conclusions

The reported experiments and the comparison made allow to state that the finite spread of plastic zones should be accounted for when calculating deflections in the post-elastic range at uniformly increasing loads.

Deflections in the post elastic range are influenced by work-hardening. At deflections of the order of the beam depth a marked increase of the load carrying capacity is observed even for beams with supports allowing for horizontal displacements. In Fig. 12 the respective curves are traced which account both for hard-

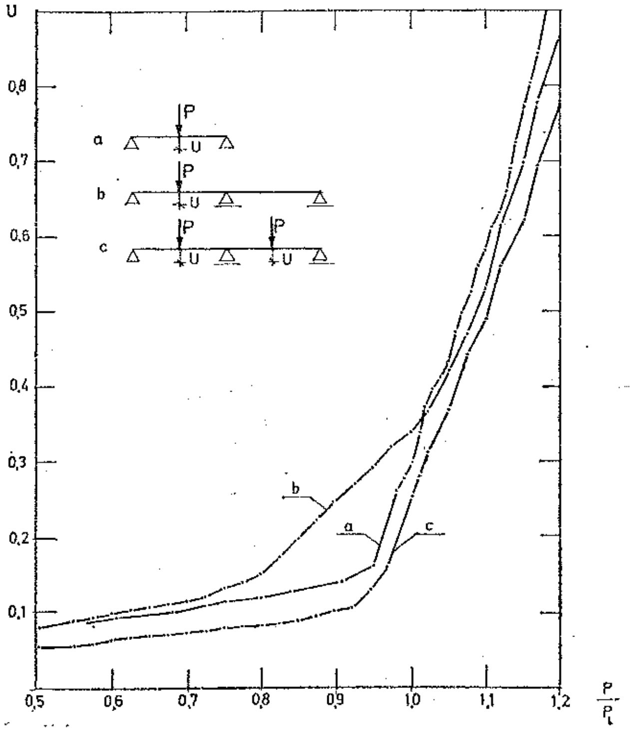

Fig. 12. Deflection thickness ratio.

ening and the post-yield action. It can be noted that the influence is more pronounced for the double span beam loaded in one span. Large rotations in the plastic hinge located at the support is felt mostly responsible for strain-hardening of the structure. This can also be concluded from Fig. 12 where the lines regarding single and double span beams approach each other. Neglecting hardening both in yield point evaluation and in deflection estimation leads to safer structures.

The presented results of systematic tests allow to get some insight into the behaviour of elastic plastic structures beyond the yield point load. The test stand and the loading techniques permit tests on the behaviour of beams under repeated loading.

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STRESZCZENIE

POZASPRĘŻYSTE UGIĘCIA BELEK PRZY PROPORCJONALNIE NARASTAJĄCYCH OBCIĄŻENIACH

Przedstawiono wyniki badań doświadczalnych belek jednoprzęsłowych i dwuprzęsłowych w obszarach odkształceń pozasprężystych przy proporcjonalnie narastających obciążeniach. Porównano wyniki badań doświadczalnych z wynikami teoretycznymi otrzymanymi różnymi metodami oceny ugięć. Można, z porównania wyników wnioskować, że wpływ skończonego zasięgu stref plastycznych powinien być uwzględniony w analizie pozasprężystych ugięć belek.

Резюме

ПОЗАУПРУГИЕ ПРОГИБЫ БАЛОК ПРИ ПРОПОРЦИОНАЛЬНО НАРАСТАЮЩИХ НАГРУЗКАХ

Представлены результаты экспериментальных исследований однопролетных и двухпролетных балок в областях позаупругих деформаций при пропорционально нарастающих нагрузках. Результаты экспериментальных исследований сравнены с теоретическими результатами, полученными разными методами оценки прогибов. Из сравнения результатов можно сделать вывод, что влияние конечного радиуса действия пластических зон должно быть учтено в анализе позаупругих прогибов балок.

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