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DISCUSSION ON THE 6th WORKING SESSION

Chairman : Dr. D. SFINTESCO

D. SFINTESCO :

Dr. Milek will tell us what has been decided at the last CRC meeting on the matter of column strength, so he brings very fresh news from CRC.

W. MILEK :

My comments constitute a report on the position of CRC in the U.S. on the maximum strength concept at multiple column curves. There have been several meetings and considerable informal discussion and I must say that there have been honest differences of opinion which are not yet fully resolved.

We all here have had an opportunity to hear presentations on recent developments during the last two days and in my opinion it is evident that a great deal of progress is being made toward refined knowledge of the strength of pin-ended, axially loaded columns. I also think that it is apparent that the subject has not been exhausted. There are still questions that need further study. Particularly, further study is needed on columns in real structures as contrasted to the pin-ended columns.

The consensus of task group 1 of CRC, based upon their own discussions which is consistent with the discussions that have taken place here, is that CRC in the U.S. take the position that there is much new knowledge about the strength of columns which need to be reported to the professionals. But in view of the several important factors which have not been studied, it is too early to make recommendations for revision of our design procedures. Knowledge that now exists will be presented in the guide as suggestions needing further review.

Now what are the principal things that we now know ? It has been amply demonstrated that given adequate information -that is relative to the mechanical properties, the magnitude and distribution of residual stresses which includes the method of manufacture, the geometry of the cross section, the out-of-straightness-maximum strength gives a highly accurate estimate of the true pin-ended column. It is also known that each of the above factors has a significant effect on the strength of the columns, therefore procedures which do not include all parameters involve errors in the estimate of strength. Scatter band for columns in general is quite broad, as shown by several of the slides today.

One method for improving the accuracy and design procedures would be to use multiple column curves in which geometrical factors and method of manufacture are taken into account in an approximate way by these several column curves. Prof.

Johnston has just proposed an alternate procedure as have the two earlier speakers. This may provide an alternate, perhaps more practical approach. Third, it is know that the tangent modulus concept provides good estimate of strength for stainless steel and aluminium structural members therefore probably should not be discarded.

What are some of the factors that merit more studying ? Basically the principal questions involve the fact that more information needs to be developed relative to actual columns in real frames as contrasted to the pin-ended columns which are certainly excellent for a laboratory tool but are very rarely encountered in real structures. Some of these items are :

1) *the work completed includes only bi-symetric cross sections. Design recommendations would be silent on asymetric sections or would require some sort of arbitrary assignment to a particular column curve. Such asymetric cross sections are important, for example single angle struts or T chords of trusses. At the present time we really have no good recommendations under the new concept.*

2) *The bulk of the residual stress measurements have been made on relatively light sections. Limited work has been done on very heavy sections thus the statistical analysis for the third curve, the lowest curve is based on a rather population. Also there is a significant gap in material thickness between the sections that have been studied and constitute the background for column curve 2 and the thicker sections that are the background for column curve 3. I believe the thickness range that jumps from 1 1/2" thick to about 3" thick is important. More information is needed over the full range of thicknesses in use. We need to answer the question if there is a threshold of thickness or, more logically, a transition between the light and heavy sections.*

3) *More information is probably needed on the effects of straightening procedures. Is it justified to design straightened sections at a higher stress than the non-straightened sections ?*

4) *Some work has been done on the effect of through thickness variation and residual stresses and it has tentatively concluded that it does not have a profound effect. Therefore as a simplification, conservative assumptions of uniform residual stresses equal to the surface value have been used in the work to date. Possibly more study is needed especially on the very thick cross sections.*

5) *The work completed is limited to pin-ended columns, which are structural elements which are useful in the laboratory as a starting point for design of compression members. However, such members do not occur in real engineering structures. There is always some end restraint which is important and it is not rational to overly refine the knowledge of pin-ended laboratory columns without parallel study of the effects of other parameters in real structures.*

6) *The maximum strength concept incorporates out-of-straightness in the length or as a length times some factor. Bjorhovde reports that the single most important variable was this out-of-straightness factor. Use of the single out-of-straightness factor L/1000 works fine in pin-ended laboratory columns. On the other hand incorporation in a design formula for real columns in structures is probably not logical for three reasons. First, in beam columns the effect of out-of-straightness diminishes rapidly as the moment increases by reason of the interaction formula. Second, it is common practice in design to modify actual lengths of restrained columns to an equivalent pin-ended column by use of the equivalent length approach. This involves that by multiplying the length by a k factor, by including out-of-straightness in a pin-ended column strength formula, the out-of-straightness would also be increa-*

sed. This just does not seem logical. Also, in high strength steels the out-of-straightness factors are more important. These questions do need study. Perhaps out-of-straightness should be handled as some sort of a separate corrective factor.

7) *It has been demonstrated that interaction formulae give good estimates of strength in beam columns. If the design rules for simple columns which in effect are an ingredient in the interaction formulae are changed, the accuracy of the results of the interaction formulae would obviously also be affected.*

8) *Elastic-plastic stress/strain properties used in the designs and studies today and possibly the influence the knee in the stress/strain curve on column strength followed by strain hardening for thick-steel sections have not been evaluated, but may be important in some structures.*

As a result of the above considerations, -what we do know and what appears to require more study- the CRC in the U.S. has decided that the three column curves as they have been suggested here will be included in the guide. They will be presented as best fit for the particular sections used in the research. The ECCS curves will also be included and the mathematical representations of these curves will be included, but column curve selection tables will not be included. In other words the intent is to present a as complete information as possible on the present state of knowledge but recommendations for implementation in design will not be included.

D. SFINTESCO :

Thank you for this most comprehensive report, which shows us that on many points we still need more knowledge and that we are far from having solved every problem, even in this limited field of the pin-ended column. Now may I call for comments on the first paper, of Marek and Skaloud ?

Ch. MASSONNET :

Thank you for giving me permission to make some remarks about all the papers before leaving because I have to take the train back to Belgium. I was struck by the phenomenon that many of us seem to like to obtain analytical representations of the buckling curves. This is of course natural for many reasons, one of these is that it is much easier to enter an analytical curve into a computer for design work for instance. Now, many proposals have been made, among others the Perry-Robertson and a nice model by Prof. Vogel, and previously also the Dutheil approach. All of these approaches are very good ; now, to decide between them, you could proceed as follows : (and this work has been done in Liege some years ago but not on a full basis) you use the least square method of curve fitting and you study which of these analytical representations gives the minimum of the sum of squares. Now a paper along this line has been written and presented to ECCS Committee 8 by one of my collaborators, Mr. S. Baar, and he has found that, of all the algebraic formulea representing the European column curves (a,b,c), the Dutheil approach had the best mathematics. Now, if any of you are interested in this paper, it should be easy to have some copies and to send them to you.

D. SFINTESCO :

Thank you Prof. Massonnet and if I may add something to your particular comment, I shall certainly not be against what you just said about this approach but I should like to complete in some way what has been reported by Dr. Dwight before on the remark of Sir John Baker saying that the Europeans did a good job because it fits with the Perry-Robertson formula. I should say they probably have done even a better work than Sir John Baker thinks, because this approach seems to fit with several formulae and it is obvious that in some areas of the world, in some countries, people, for various reasons, would like not to change the theories to which they are accustomed as far as they can fit with the practical results and I think this is by no means bad.

Now, are there any comments on the second paper by Bjorhovde and Tall ?

J. BROZZETTI :

I would like to ask some questions to Dr. Bjorhovde and Dr. Schulz. We saw two proposals for multiple column curves but if we study particularly these proposals we can see some differences between the two. For example in the Lehigh proposal one curve stands for annealed sections. Instead in Dr. Schulz and Prof. Beer's work you have two curves, depending upon the bending axis. I would like also to make another comment about the lowest curve presented by Dr. Bjorhovde. I think people have a slight tendence to put too much residual stresses in those very heavy shapes. As far as I remember we made some measurements at Lehigh about the 14 WF730 and we never got so much residual stresses in this heavy shape. I don't understand why you have a so low curve. Dr. Schulz said that in fact the magnitude and the distribution of residual stresses change with the amount of welding. I am not quite sure about that, because we have several experiments also at Lehigh and our conclusion was that the speed of welding did not have a very significant effect on the residual stresses due to welding. I would like to have some answer about these questions.

R. BJORHOVDE :

With regard to Mr. Brozzetti's question about the assignment of major and minor axis bending of annealed shapes to the same column curve, the answer is simply that the differences in major and minor axis strength were too small to warrant placing the two cases in different categories. This applies to the development of the American multiple column curves, which was done somewhat differently than in the European study. As you can see, curves a and b of the European proposal are much closer together than our curves 1 and 2, and henceforth much smaller differences in strength would cause a change in the classification. Although the number of annealed shapes that was included in our study is not statistically large, I believe that the assignment of annealed shapes to the uppermost of the three curves is substantiated by their classification in the European proposal. Mr. Brozzetti's comment about the residual stresses in the W14 × 730 shape is not quite relevant, since the shape he measured was found to have been cold-straightened. Finally, I would like to agree with Mr. Brozzetti in his statement to Dr. Schulz that the magnitude and distribution of the residual stresses do not change with the amount of welding. Our studies at Lehigh University over a number of years have proved that conclusively.

G. SCHULZ :

Dr. Bjorhovde already indicated as one of the reasons the different distance between the European and the American curves. But there is another reason for the discrepancies in placing sections in appropriate column design curves. It seems that for the American and the European version of the column curves, there is quite a difference in the philosophy that led to their establishment. The American curves are based on L/1000 as the European curves, but the selection of the three curves was done quite differently. For the selection of each of the American curves, a wide band of column curves was plotted and the mean value out of this band was selected. The European curves were established according to the philosophy on which the evaluation of the tests were based. They do not correspond to the mean value, but to the mean value minus 2 × the standard deviation.

L.S. BEEDLE :

Mr. Brozzetti commented about the residual stresses he measured in a 14 WF 730. Of course that shape was cold straightened which would reduce the residual stresses below what Dr. Alpsten would have predicted. That in fact is one of the reasons why further studies are needed on the effect of cold straightening, as Dr. Milek has emphasised.

J. BROZZETTI :

Yes I agree with Dr. Milek's work but as far as I remember we had several discussions with Alpsten and I did not agree too much with him about the theoretical predictions he gave in one of his reports. His predictions were quite unfavorable, and as far as I remember on some diagrams you have almost one tenth of the shape which was already yielded ; but we never find these results when we measure the residual stresses in some of those heavy shapes.

L.S. BEEDLE :

Because what you measure is the residual stress in a cold bent shape.

J. BROZZETTI :

Yes I agree but in fact it was partly straightened. I do not know if you remember Dr. Beedle but it was only the flange which was partly affected. It was not the entire shape I guess.

R. BJORHOVDE :

The W 14 × 730 shape which has a flange thickness of 5 inches was cold straightened, or there was at least very strong evidence to that effect. Concerning the residual stresses that may occur in non-straightened members of that size, there are indications from the measurements of heavy plates that these correlate well with the magnitude of the residual stresses that one may expect to find in heavy unstraightened members. These results compare favorably with the studies that were made by Dr. Alpsten. For example, at the edge of a 6 inches thick universal mill plate of material with 36 ksi yield stress one will find a compressive residual stress of approximately 28 to 30 ksi. This stress is considerably higher than that measured in a W 14 × 730 shape, where the maximum compressive residual stress was about 18 to 20 ksi.

J. BROZZETTI :

Yes but, I think you agree with me, we never find in those rolled plates any residual stresses reaching the yield point ; in fact we find up to 2/3 of the yield point, that's all. I would like to ask another question. I don't understand why you have some differences between the curve b as proposed for example in the general Lehigh approach and the experimental curve of ECCS. In fact both apply to the same case and I do not see why you have a difference between them. If the theory does not agree with the experimental curve we should retain the experimental curve and not the theoretical one, this is my point.

G. SCHULZ :

Well, If I follow you, you are referring to the experimental curve of ECCS and curve b of ECCS. Well, there is no difference between those two curves.

D. SFINTESCO :

May I mention just the story of this thing. We had quite long discusssions at the European Convention about this particular point because in a previous presentation of the Graz results the curve b was not so near the experimental curve. We discussed for some long time about that and as a consequence some adjustments were made in the program in order to put the curve in accordance with the experimental results. I agree with Dr. Schulz's position for the present situation.

G. SCHULZ :

There was originally, I guess this was 1966 or earlier, a first suggestion with four column curves. Curve 2 of this proposal did not agree in the low slenderness range with the experimental curve. There was a deviation of two or three percent. When we had to reduce the number of curves to three, the present curve b was introduced, which agrees quite well with the experimental curve.

D. SFINTESCO :

As a matter of fact in the first version of this curve b which we have discussed at the European Convention there were two differences : in the range of the lower slenderness ratios the computed curve was lower and in the higher range it was higher than the experimental points. It has been adjusted in the meantime and we have now a fairly good agreement between the two curves. So maybe Brozzetti is referring to the older version of these curves.

G. SCHULZ :

Mr. Chairman, may I answer to the question Prof. Dwight was asking Prof. Massonnet with regard to the sections of high strength steel ? We did not recognize the reduced influence of the residual stresses due to the higher yield point, therefore, the suggested curves are slightly conservative for rolled sections of high strength steel. The slide shows that the gain in column strength which was omitted is very small. In particular, for the sections of high strength steel presently used in Europe, the gain is too small to make the jump into the next higher column design curve.

D. SFINTESCO :

Dr. Schulz, we have seen that in your program, you have used what I would call an idealized pattern of residual stresses with symmetrical distribution. However, in all residual stress measurements made either by Prof. Massonnet or at Lehigh, in fact everywhere, we always see a non-symmetric distribution of the residual stresses. Now one can think that the symmetry of distribution of these residual stresses may affect the buckling process itself. Did you make any trial to see how it works with a non-symmetrical distribution ? I think it should have been possible with your program.

G. SCHULZ :

No, it is not possible because we consider only the bending in the direction of one axis. As long as we do not consider biaxial bending we probably won't be able to get a significant gain in column strength due to an unsymmetrical residual stress pattern.

D. SFINTESCO :

Well of course any mathematical model cannot reproduce all irregularities which exist in reality, but I think this may not be a minor effect for the phenomenon itself. I wonder if it should not be investigated.

G. SCHULZ :

It could be done. But actually, if the conditions are extremely unsymmetrical, we should not anymore apply the theory of pure flexural buckling.

R. BJORHOVDE :

Mr. Chairman, a comment to your question on the effects of an unsymmetrical residual stress distribution. A study was made by Gernot Beer when he was studying at Lehigh University, and he found that unsymmetry in the residual stress distribution was quite insignificant. In this particular study Mr. Beer investigated the strength of box sections.

D. SFINTESCO :

Well, the effect may be different for I sections.

G.C. LEE :

I think the question of unsymmetrical residual stress can best be lumped into the geometrical imperfection parameters. It is difficult to see how a perfectly straight or nearly straight member can have unsymmetrical residual stresses.

T. BARTA :

I think the question about the asymmetric distribution of residual stresses might be important if one thinks of flexural torsional buckling but this has not been considered by the team in Graz and this will obviously play in some stage of higher slenderness. We have made a couple of years ago an attempt to generalize imperfections by taking fine imperfections for flexural or torsional buckling. This can be done by the Perry-Robertson or by any other variant and by adjusting to test results and this probably would agree better with assymmetric distribution of residual stresses.

D. SFINTESCO :

As a matter of fact in the experimental series of tests of the European Convention even for members which were on knife edges we have measured the torsion at mid height and there was always some torsional effect. We have records of these measurements.

May I now call on comments on Dr. Dwight's paper.

M. MARINCEK :

I think that the dimensionless buckling curves have an advantage.

O. STEINHARDT :

I have a remark to the paper of Prof. Vogel and also to the last note of Prof. Marincek. The effective-length-method, as a reasonable approach for the determination of critical buckling loads of single story frames, on the one hand is too safe in some cases, that is the statement of Dr. Vogel. In my opinion it is not sure that on the other hand for clamped single storey frames with drift influences by outside columns, this definition could be used. In special cases we have found that (without some additional explanations for the plastic configuration !) the safety margin for the whole system may be very much less, than supposed when using only the new German guiding principles. Otherwise I refer here to my paper given the last day about the same problem for Aluminium construction.

U. VOGEL :

Prof. Steinhardt I am not able to give an answer because I have not studied the frame with fixed basis on the column foot. So it could be that you are right but I cannot comment on this. I would like to take the opportunity to give an answer to the comment of Prof. Massonnet. It was not my intention to establish *another mathematical formula for the European buckling curves. I used this method only as a tool to get an idea of the order of magnitude of a representative imperfection which I could use then to treat a frame or a framed column.*

D. SFINTESCO :

Thank you, any other comment on the same paper ? Then any remarks on Prof. Johnston's paper ?

G. SCHULZ :

May I comment not on Prof. Johnston's paper but on the remarks of Mr. Milek mentioned the initial out-of-straightness as the most important parameter for column behavior and for the determination of the maximum strength. Well, this statement probably has to be modified. The out-of straightness is another important factor, but its influence is definitely smaller than that of the residual stresses, and depends very much on the magnitude of the residual stresses which are present in the section. For sections with high residual stresses the influences of a variation of the out-of-straightness is comparatively small.

R. BJORHOVDE :

I would like to comment on what Dr. Schulz said. As far as the out-of-straightness is concerned, I think Mr. Milek was referring to the part of my study which was dealing with the probabilistic nature of the maximum strength. I think I again should point out that when the column strength variables are treated as random variables, and henceforth producing a random variation of the maximum strength of the column, that is when the initial out-of-straightness attains its greatest importance. It by far supercedes the importance of the residual stresses when their random or variations about the mean are being included in the analysis. Again, we are here talking about the random variations that occur in a number of samples of identical shapes. Thus, Dr. Schulz and I are covering entirely different matters. I also think that Dr. Johnston might want to add a few words relative to the importance of the initial out-of-straightness and the residual stresses.

D. SFINTESCO :

Well, gentlemen, thank you for your interesting comments. I suggest we adjourn more or less in time, as we shall have now our closing session with summaries by the chairmen of the sessions. Thank you.