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Inaccuracies In Construction

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J.K. Latta

Please note

In combining two or more separately manufactured parts to produce a finished article, it is obviously necessary that the parts be made to the right size. Absolute precision is not required, and in the vast majority of cases inaccuracies in manufacture can be allowed for by suitable gaps between components. If these are not too big, they can subsequently be filled, if need be, with some moulded-in-place or elastic component. The crux of the matter is to determine what constitutes "too big" and what deviations from precise dimensions are tolerable.

In traditional structures the problem was overcome by forming the members in place or by cutting them to fit on site. Nowadays, more components are manufactured off the site. Before they can be installed, however, they or the components with which they mate often have to be modified in some way. This is akin to the earlier days of mechanical engineering when components had to be hand fitted into a machine. Now it is possible to machine to a high degree of accuracy, thereby ensuring the proper interconnection of parts, and this has eliminated a time-consuming process that required great skill. It has opened the door to mass production and reduced costs. Similarly, if more accurate methods of manufacture could be developed in building construction, both on and off the site, much waste of effort and material could be avoided.

There are three basic sources of inaccuracy in building construction: setting out, the dimensions of a manufactured component, and the positioning of that component (including in-situ work). Possible values for the inaccuracies arising from such sources are given in Tables I to VI.

Setting out comprises the establishment, on site, of a convenient reference system for controlling the alignment and level of building elements and locating a structure shown on a drawing. The degree of accuracy that can be obtained depends upon the type of measuring instrument and to a great degree. upon the skill and conscientiousness of the operator. With simple instruments such as spirit levels and pocket rules, the level of skill required is not very high. For optical and other more precise instruments, however, it is important that they should be used by suitably trained operators and competent assistants.

For linear dimensions the 100-ft steel tape is normally the best instrument, accuracy of measurement depending on such things as slope, sag, temperature and tension. If a high degree of accuracy is required, corrections must be made for all of these; but provided that the tape is supported to eliminate most of the inaccuracy due to sag and that extremes of temperature are avoided, only corrections for slope need generally be applied (see Table I).

Table I. Linear Dimension Accuracy

Distance	Accuracy
Up to 10 ft	±1/8 in.
10 to 100 ft	±1/4 in.
Over 100 ft	Pro rata

The most usual angle to be set out is the right angle and three methods are normally used (the last can be used for any angle). With a steel tape, the right angle can be determined by the construction of a 3:4:5 triangle, or the diagonal of a rectangle of known sides can be calculated. This method is satisfactory for houses and other small buildings. The second method, the traditional optical square, makes use of prisms or mirrors, but it is not sufficiently accurate for use in building. The third method employs the transit or theodolite, and provided it is used correctly it is the most accurate means of setting out angles of any size (Table II).

Table II. Accuracy In Setting Out A Right Angle

Method	Accuracy
Steel tape	2 min of angle (±3/4 in. in 100 ft)
Optical square	15 min of angle (±5 in. in 100 ft)
Transit	
Vernier (20-sec cal)	40 sec of angle (±1/4 in. in 100 ft)
Micropter (20-sec cal and optical plummet)	20 sec of angle (±1/8 in. in 100 ft)

Several methods of obtaining verticality are available, depending upon the height involved and the degree of exposure to wind. Heavy plumb-bobs can be used for heights up to 10 ft, and with special precautions such as immersion of the bob in liquid and protection of the line against wind, for heights up to 30 ft. Only in completely sheltered situations can they be used with confidence for greater heights. Transits are used in two ways to define verticality: either by setting up away from the element to be plumbed and elevating the telescope to sweep its full height or by optical plumbing. In either case precautions must be taken to eliminate instrument error, Optical plumbing instruments are available that are specially designed to perform the same function as optical plumbing by transit. The techniques are identical and the same precautions should he taken. In general, these instruments give greater accuracy and can be used over any height. The accuracy obtainable with each method is given in Table III.

Table III. Accuracy In Verticality

Method	Accuracy

Spirit level	±1/4 in. in 10 ft
Plumb bob (still conditions)	±1/8 in. in 10 ft
Transit (optical plummet)	±1/8 in. in 100 ft
Optical plumbing device	±1/16 in. in 100 ft

Vertical dimensions or levels can be established by several methods with varying degrees of accuracy (see Table IV). Spirit levels used in conjunction with straight edges make it possible to transfer levels over distances of up to 20 ft horizontally. Water levels are slightly more accurate than spirit levels and can be used over distances of 30 ft. Optical levels are the most common means of establishing levels accurately, but they are not reliable over distances in excess of 200 ft; because cumulative inaccuracy can arise they should not be used to transfer level datums vertically. It is preferable to use a steel tape to measure up the face of a column or wall from a benchmark at its base.

Table IV. Accuracy In Level

Method	Accuracy
Spirit level	±1/4 in. in 20 ft
Water level	±1/8 in. in 30 ft
Optical level	±1/8 in. in 200 ft (±1-1/4 in. per mile)
Precise level	±1/16 in. in single sight (±1/4 in. per mile)

There is also the question of the pressure of time, which frequently works against the dictates of accurate setting out. With correct techniques the effect of instrument inaccuracy can be limited. although this usually requires a little more time. Working conditions should be favourable in order to reduce reading errors, i.e., illumination should be good, there should be little wind temperatures should be moderate and the weather dry. If weather conditions are bad and accuracy is important, it is better to defer setting out until conditions improve. All calculations and all measurements made on site should be checked. If they are particularly important they should be checked by a second person using, if possible, a different procedure, for example, by measuring from a different grid line or a different benchmark.

All of this discussion relates to normal setting-out methods, using conventional instruments. Much greater accuracy should be possible with modern instruments such as lasers. Although not yet used extensively except for tunneling and similar civil engineering applications, they are being adapted to building operations.

Once the position in which an item is to be placed has been located, one must take into account the inaccuracies in the item itself, be it manufactured or an on-site construction operation. Items manufactured off the site in the relatively controlled conditions of a factory should be, and in general are, made more accurately than comparable items made on site. Even so, there is usually a difference between the actual dimensions and those specified, and this difference is frequently much bigger than anticipated.

Two studies carried out within the past seven years, one in Britain and one in Denmark, showed that with precast concrete units the actual deviations in dimensions were between two and three times greater than the tolerances specified. Both studies were on precast units for system building, so that it may be taken that the production runs were long enough for good quality moulds to have been used and some system of quality control to have been instituted. Both showed that deviations of up to ±3/8 in. could be expected in the length or breadth of panels and that this was largely independent of the over-all dimension, up to about 20 ft. This can be compared with the 1/8- or 3/16-in. tolerance in a 10-ft length that is often specified.

In the British survey it was also observed that the wall panels were located in relation to one another by means of holes in the lower edge of the upper panel that engage with bolts projecting upward from the upper edge of the lower one. It was found that the maximum likely deviation in the position of the holes was 5/16 in. longitudinally and 1/4 in. transversely. As the position of these holes was critical to accuracy of assembly, it was taken that the deviations had occurred despite serious efforts to minimize inaccuracy.

If such inaccuracies occur in panels cast in a factory, what about cast-in-place items? Unfortunately, and perhaps surprisingly, accurate information is often absent. Only where there is extensive off-site fabrication of major components and use of industrialized building systems has much attention been paid to it. The craftsman's technique of cutting to fit on site no doubt dealt with the problem satisfactorily before. This is strikingly similar to the situation in mechanical engineering production before modern techniques were developed.

In 1962, the American Concrete Institute formed a committee (No. 117) to investigate the problem of tolerances in building construction. After finding that factual data on the subject was virtually nonexistent, the members chose a building representative of high quality construction and measured parts of it to determine, among other things, the variations in column location. Some of their findings are given in Table V.

Table V. ACI Committee Findings Concerning Position of Concrete Columns

Column Location Deviations	Usual	Maximum
Individual column from its line	±1 in.	±2 in.
Spacing between parallel column lines	±1 in.	±2 in.
Squareness between perpendicular column lines	1/8 in. in 10 ft	1/4 in. in 10 ft

Some years ago, the Division had the opportunity to measure the width of the joints between 25-ft wide precast concrete wall panels on six floors of a 30-storey building. The results of this "one shot" survey are given in Table VI, from which it may be seen that the joint widths varied from zero, or near zero, to 3/4 in., a variation of ±3/8 in. about the specified joint size of 3/8 in.

Table VI. Joint Widths On Six Floors of A 30-Storey Building

Joint Width, in.	No. of Joints
0-1/8	3
1/8-1/4	17
1/4-3/8	42

3/8-1/2	24
1/2-5/8	7
5/8-3/4	3
Total joints measured =	96

Once an estimate has been made of the various inaccuracies of components to be fitted together it is necessary to combine them in an over-all variation that the joint must accommodate. If permissible deviations on each dimension were to be estimated for the worst case, the joint might have to be so large as to be unacceptable. It is highly unlikely, however, that all inaccuracies from different sources will be at a maximum in the same direction for any one component, and in calculating a total tolerance a certain degree of probability should be assumed. It must be realized that in doing this some cases may occur in which the desired fit is not obtained, even when individual deviations are within the specified limit. In such cases it will be necessary to select components or "cut to fit" on site, but occasional cases of this sort are probably preferable to extra-large joints.

Tolerances that develop independently in individual components can be combined in an over-all tolerance by taking the square root of the sum of the squares of the individual values.

$$T_D = \sqrt{t_a^2 + t_b^2 + t_c^2 + \ldots}$$

where T_D = over-all tolerance in one direction,

and

t_a, t_b, t_c ... = tolerances or inaccuracies from different sources.

For a run of components the same statistical method can be used to calculate the combined effect of tolerances on individual components:

$$T_{D0} = \sqrt{T_{D1}^2 + T_{D2}^2 + T_{D3}^2 + \ldots}$$

where T_{D0} = combined effect of tolerances on individual components, and

T_{D1}, T_{D2} ... = tolerances on individual components.

This method of calculation makes no allowance for the fact that, in practice, the effect of inaccuracies in manufacture may be partially mitigated during erection; for example, the plumb adjusted to counteract the effects of bow. It can be used to combine only those inaccuracies that occur by chance, as a result of human inability to make anything to an exact size. variations in dimension owing to thermal or moisture movements caused by change of conditions must be estimated independently and added arithmetically for any anticipated set of conditions.

Conclusion

In general, it is probably reasonable to say that the standard of accuracy thought to be attainable in building construction is often much higher than that actually attained in practice. Such a statement is not intended to be a criticism of the building industry. It implies, rather, the need for designers, specifiers and constructors to be more realistic about the situation. Designers may have to accept the present standard of inaccuracy as a fact of life and design all facets of the building in such a way that errors can be accommodated in construction without expensive and time-consuming remedial measures on site. A design that demands higher accuracy than can normally be attained will inevitably be more troublesome to build. Specifiers should not call for unnecessarily tight tolerances; they will only lead to an excessive number of rejections or to protracted arguments. In turn, constructors should review their present practices with a view to minimizing inaccuracies. If only the gross errors were eliminated, or even if they were detected at an early stage, many a job would run more smoothly.