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Appraisal of Existing Ferrous Metal Structures

Examen de constructions en fonte et en fer

Begutachtung bestehender Eisenkonstruktionen

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SUMMARY

The investigation of structures built since the late 18th century will often demand the appraisal of loadbearing members of cast iron, wrought iron, or steel. The paper considers the various aspects of such an appraisal, and in particular emphasises the need for an understanding of the original materials and their characteristics, construction methods, and design standards.

RESUME

L'examen des ouvrages construits depuis la deuxième moitié du XVIII^{e} siècle exige souvent l'évaluation des éléments de charpente en fonte, en fer forgé, et en acier. L'article traite les divers aspects d'une telle recherche, et particulièrement de l'importance de la connaissance des matériaux originaux et de leurs caractéristiques, méthodes de construction, et modes de calcul.

ZUSAMMENFASSUNG

Die Untersuchung von Gebäuden, die seit Ende des 18. Jahrhunderts gebaut wurden, verlangt oft eine Begutachtung tragender Elemente aus Gusseisen, Schmiedeeisen oder Stahl. Die verschiedenen Aspekte einer solchen Begutachtung werden diskutiert, und insbesondere wird die Notwendigkeit betont, die ursprünglichen Baumaterialien und ihre Eigenschaften sowie die Baumethoden und Entwurfsnormen zu verstehen.

1. INTRODUCTION

There is at present a growing tendency for old buildings to be renovated or adapted for re-use. In itself this is not a novel situation, but it is significant that many of these were constructed during the last two centuries, in the period which has seen the introduction and widespread use of first cast iron, then wrought iron, and ultimately steel as structural materials. Consequently the engineer is likely nowadays to be faced more often with the appraisal of structures containing one or more of these ferrous metals.

The aim of the appraisal will be to show whether the structure can be retained for the future intended use of the building, whether it needs to be strengthened, or whether total renewal is the only practical course of action. Factors other than purely structural considerations will of course also need to be taken into account: these include for example adequacy of storey heights, and legal requirements for preserving architecturally important facades.

It is worth stressing here the contrast between design and appraisal, which is particularly relevant in regard to ferrous metal structures. In a design, the engineer can prescribe through drawings and specifications the material properties, member sizes, and construction details to ensure that his (usually simplified) assumptions of strength and behaviour are achieved in the built structure. An appraisal however is concerned with a structure that has already been built: its characteristics exist but are initially unknown and must be defined by investigation of the structure itself, coupled with an awareness of the original materials, and design and construction practice of that time.

2. GENERAL APPRAISAL PROCEDURE

The appraisal process generally involves investigation and assessment in two stages, broadly analogous to the 'scheme' (or preliminary) and 'detailed' (or final) stages in the design process.

The aim of the preliminary appraisal is to establish in principle whether it is feasible to retain the existing structure for the future. (If the answer to this is 'no' there is clearly no point in making any further study.) This stage involves:

- search for available drawings and other documentary evidence
- identification of the metal(s)
- outline structural survey to establish existing construction thickness and spans, member sizes, and major defects
- preliminary assessment
- decision in principle on feasibility of retention

The timescale for this preliminary appraisal is often very short, being imposed by the building owner or client. This can paradoxically be of benefit in helping to focus attention on generalities rather than particulars of the structure, in encouraging the minimum and simplest of calculations, and in postponing the commissioning of slow and expensive detailed surveys and testing programmes. (In this stage it is suggested that any testing of materials is done only to confirm the identification of the metal(s).)

The final appraisal, once the feasibility of retention has been established in principle, will be a more thorough exercise involving:

- detailed structural survey of all construction that is required to remain (especially connection details)
- detailed definition of renovation and re-use needs as they affect the structure
- testing of materials
- comprehensive assessment of members and connections
- decisions in detail on strengthening and other alterations to structure

Following this, the necessary work can be specified.

It should not need saying that the early involvement of the building control authority is essential in any appraisal for alterations or re-use in which it can exercise statutory powers, for it - as well as the engineer involved - must be satisfied that the existing structure has been properly investigated and realistically assessed, and it would be foolish as well as time-wasting to develop a detailed scheme which is then rejected on submission to the authority because of fundamental disagreements on approach.

The rest of this paper concentrates on specific aspects of the appraisal of ferrous metal structures, namely: identification of the metal, preliminary assessment, testing, and final assessment. The general principles and approach to be applied in any structural appraisal have been described elsewhere (e.g. [1]), and are not discussed further here.

3. IDENTIFICATION OF THE METAL

3.1 Visual Aids to Identification

Distinctive features to aid in the recognition of cast iron members are:

- pitted or 'gritty' surface (from the sand or loam mould)
- thick or coarse cast sections
- 'flowing' sections and profiles (e.g. solid and hollow circular, and X-and H-shaped sections; 'classical' column heads with integral endplates; shaft entasis)
- bottom (tension) flange larger than top flange
- beams of inverted T- or V- section
- bottom flange of beams often curved on plan or elevation
- internal corners rounded (to deal with cooling shrinkage stresses)

Connections between cast iron sections were by simple bearings or by wrought iron threaded rods and nuts fixed through pre-formed holes. Hollow circular columns were often cast in two semi-circular pieces which were then brazed together.

Wrought iron resembles steel in being formed into structural sections by passing billets through rollers. The earliest beams were built up from plate and angles rivetted together. Subsequently rolled beams became available, often being strengthened by rivetted flange plates and web stiffeners. Its tensile superiority over cast iron led to its early use as chains, cables, and links for suspension bridges, and as tie-rods in buildings. The rods were frequently employed compositely with cast iron to form trussed beams and roof trusses.

Wrought iron can be distinguished visually from cast iron by its smoother rolled surface - assuming that not much corrosion has occurred. If more corroded, wrought iron tends to delaminate into thin sheets of nearly pure iron alternatively with slag which can be pulled away from the surface.

It is more difficult to distinguish sound wrought iron from steel as their production and structural forms are so similar. Unless there is conclusive evidence from documents or dating as to which metal is present, it is best to take small samples for identification.

3.2 Dating Evidence

The chronology of iron and steel use in structures is fairly well-defined, although dates vary between one country and another. In the UK, for example, cast iron was used between the 1790s and the early 20th century (columns only after about 1860); wrought iron from 1840 (built-up beams from plates and angles) and 1860 (rolled I-beams), being obsolete by 1914; while steel was introduced structurally in the late 1870s and subsequently was the only ferrous metal used in new construction after 1914.

Thus, if the building can be dated by documentary and/or stylistic evidence, it should be possible to distinguish between wrought iron and steel, except in the 'overlap' period when both were in use. Care in relying on dates is obviously needed when a structure has been altered since construction.

3.3 Sampling for Confirmation

It is necessary to take only a small sample of metal, for chemical and metallurgical identification by a specialist testing house. A 25mm square piece core-drilled from a lightly-stressed location will be adequate for this purpose. In the case of cast iron it is important that identification includes the particular type of cast iron as these have significantly varying properties.

4. PRELIMINARY ASSESSMENT

4.1 Approach

It should be recognised that material specifications, methods of quality control, and regulations covering design and loading, have only recently been developed into the rigorous and numerically-orientated instruments that they are today. It is therefore not appropriate to appraise a 19th century structure of cast or wrought iron by calculations based on a modern steelwork code of practice, even if suitably factored to recognise a different basic stress, not least because the characteristics of these materials as manufactured then are not consistent with those of today's steel.

Nevertheless some simple calculations must be made to establish an idea of member strength and hence the feasibility of re-use. If these are to be relevant, the engineer needs an understanding of material quality and contemporary practice at the time of construction.

4.2 Material Quality

Cast and wrought iron, and early steels, were seldom produced to a nationally defined standard as is steel today. Instead, each ironworks would offer a variety of grades suited more or less to the needs of its market. Extensive testing was carried out on these, and the results were published in commercial literature and textbooks. Quoted strengths were usually at ultimate (breaking) load.

A study of test results for any grade generally reveals considerable variability in strength, which was accommodated by correspondingly large factors of safety (between 3 and 10) for working use.

4.3 Original Design Practice

Before building legislation laid down allowable stresses in structural metals, design was based largely on experience and elementary structural theory. These are frequently to be found in the contemporary textbooks, which in many cases can be regarded as the equivalent of modern codes in recording good practice, as well as providing an invaluable reference source on construction details.

Where building legislation had laid down a design approach and quantified allowable stresses, and was in force at the time of construction, it is reasonable to assume that the structure would have been designed to comply with this, which may be used as a present-day standard for appraisal. (Some building control authorities will indeed require such an approach.) The quoted stresses in these are generally conservative, and may also be used for preliminary assessment of structures pre-dating such legislation.

4.4 Loadings

Nineteenth century textbooks show a wide variation in the allowance made for imposed loads: they were however generally higher than would be considered necessary today.

It is clear, however, that many builders did not adopt such onerous figures for domestic and commercial timber floors (which were sized by experience and/or rule of thumb), and this is probably true also of many building structures with metal beams and columns.

The fact that such structures were clearly always incapable of supporting the over-generous design loads quoted in the textbooks and yet today exhibit no signs of overloading, has led building control authorities to be increasingly reluctant to accept unquestioningly schemes for which current live loading requirements would appear to be less than the original 'assumed' loading. It will therefore usually be necessary to establish member sizes and show by calculation that the existing structure is adequate.

Wind loading on early building structures - rather than bridges - was not often considered.

5. TESTING

5.1 The Need for Testing

Once the preliminary assessment has shown re-use to be feasible, it will generally be necessary to obtain more comprehensive information on the existing structure before making the final, detailed, assessment. In particular, materials testing may be considered.

There is little point in making tests if an initial appraisal has shown that the structure is in an unsound state already, or that it is grossly overstressed in its new use. Conversely, a 'young', well-documented steel structure - and often older structures too - may need little or no testing if they are in sound condition and will be stressed only to modest levels in the future.

It is important that the building control authority requirements for testing are identified.

Some authorities are very dubious about the usefulness of testing as an indication of typical strengths in the actual structure: this may be understood by considering that manufacturing quality control in the 19th century was very much cruder than it is today, as was recognised by the generous factors of safety applied. There is thus no guarantee that sampling for testing, or even in situ load testing to failure (e.g. of elements typical of the building but unwanted in the proposed scheme), will give results that can be confidently regarded as 'average', still less as 'lower-bound', for the elements as a whole.

5.2 Criteria for Sampling

It is generally assumed that the strength of a group of similar ferrous metal elements will vary in accordance with a normal distribution: an approximation quite adequate for most circumstances. It is then possible to use statistics to give an estimated strength.

Usually this is a 95% confidence limit based on test results, i.e. a figure below which no more than 5% of the actual strengths should fall. To find this, it is necessary to calculate the mean value and the standard deviation of the test results. The 95% confidence limit will then be a number of standard deviations below the mean, that number being a function of the number of samples taken. Hence, if only two samples have been taken it will be necessary to use a value 6.3 standard deviations below the mean, whereas if six samples are taken this is reduced to 2 standard deviations. For an infinite number of samples, the figure is 1.65, so there is little to be gained by taking more than six samples.

Beams and columns may not necessarily be from the same source of supply or even of the same material. This should be established in the initial identification exercise, the number and location of samples being extended as appropriate.

5.3 Choice of Tests

The most useful information can be gained from a standard tensile test, i.e. yield stress, ultimate strength, Young's modulus, and elongation to fracture. This obviously involves destructive laboratory testing of samples cut from the structure. Ideally, samples 200 x 100mm should be cut, which will then be machined to the required shape by the testing laboratory. Samples may be removed using a hacksaw, interlocked drilled holes, or flamecutting (which should only be used with an additional 1-15mm allowance around each cut face to enable removal of the heat-affected zone). In taking the sample a prime requirement must be not to weaken the structure dangerously.

Where it is intended to weld to existing steelwork, a chemical analysis for weldability should be made. This can be done on part of a broken tensile specimen. It is in general not advisable to consider welding existing cast or wrought iron.

5.4 Interpretation

If a sufficient number of test results are obtained, the 95% confidence limit can be calculated as previously described. This should then be divided by a suitable factor of safety. For cast iron a factor of 3 is suggested in view of its brittle nature; similarly, in view of the greater variability of wrought iron, compared with steel, a factor of 3 on the 95% confidence limit of tensile strength seems appropriate.
Recent or better-quality older steel should exhibit a narrower variation in strength: the tests should also confirm whether the steel is of mild or high-tensile quality. The permissible stress adopted for appraisal should, it is suggested, be less than the minimum value of the elastic limit, and be not more than either 0.67 x 95% confidence limit of the yield stress or 0.375 the ultimate strength.

6. FINAL ASSESSMENT

The final assessment of the structure can follow one of two courses.

The first is to appraise the members and their connections using design rules and allowable stresses that were in force at the time of construction. This may be particularly appropriate for earlier structures where the in situ material strengths vary widely, and of course could also be applied in the appraisal of a more modern steel structure. The advantages of such an approach include speed and simplicity of calculation, and the high probability of acceptance by building control authorities, especially when the design rules used were prescribed by them or their predecessors.

The disadvantage of this method is that it may not be possible to justify the adequacy of all parts of the structure using the inevitably simple and conservative assumptions built into such rules. In this case it will be necessary to apply an assessment using theoretical first principles; this will inevitably be more time-consuming, and does not necessarily guarantee success in justifying the structure, but does give much more scope for the engineer to take account of the real conditions in which the particular structure will be serving, and to exercise his judgement in relating these to the analytical model he uses. This approach is particularly useful in assessing the strength of columns with varying degrees of end restraint and imperfections in line and straightness.

REFERENCES

1. INSTITUTION OF STRUCTURAL ENGINEERS, Appraisal of Existing Structures, 1980.