Rigorous assessment of existing overhead line gantries for the Elizabeth line

Simon Fryer
MEng, CEng, MIStructE, MICE
Technical Director, BuroHappold Ltd, UK

Matthew Crouchman
BEng (Hons), CEng, MIStructE, MICE
Associate, BuroHappold Ltd, UK

Thomas Eckhart
MEng
Engineer, BuroHappold Ltd, UK

Synopsis

The Elizabeth line will use above-ground sections of existing Great Eastern and Great Western tracks between Stratford and Maidenhead where new overhead line equipment (OLE) and traction power supply will be installed.

The OLE is supported by gantries of various types and configurations. In the case of the Great Eastern, the gantries date from the electrification of UK railways in the 1940s.

Initial structural assessment carried out had shown that existing gantries on the route were inadequate to carry increased loading from the upgraded OLE. However, a rigorous procedure incorporating detailed non-linear structural analysis was developed that eliminated some of the inherent conservatism in traditional codified approaches. Particular benefit was found in the case of the many types of slender structure where buckling was a governing factor. Using non-linear techniques, it was possible to demonstrate that families of structures were suitable for incorporation in the Crossrail (Elizabeth line) scheme.

This paper describes the approach that was used. The project is remarkable for significant programme and cost savings that were accomplished using sophisticated engineering analysis. It is also noteworthy from a sustainability point of view, as it allowed the existing infrastructure to be reused.

NOTATION

ATF	autotransformer feeder wire
IWC	idealised worst case
OLE	overhead line equipment
SWC	specific worst case
TPS	traction power supply

Introduction

The above-ground sections of the Elizabeth line route that extend from Maidenhead to Shenfield incorporate upgraded overhead line equipment (OLE) and traction power supply (TPS) cables that will be supported on existing OLE gantries as far as possible. Most of the gantries on the Great Eastern railway date from the electrification programme of the 1940s and may therefore be among the oldest surviving overhead electrification gantries in the country. Those on the Great Western railway are more recent, dating from the Heathrow Express electrification scheme of the 1990s.

The TPS project will install two or four new autotransformer feeder wires (ATFs) along with associated earth wires to the route. In parallel with this, the OLE on the Great Eastern is being renewed with a more modern system.

The gantries may be categorised into families of similar structural types. Common families are single masts, cantilevers, head span and portal structures, some varieties of which are illustrated in Figure 1. Most of the members making up the gantries are relatively slender rolled steel sections, either single or compound. The masts of the gantries are generally either embedded in, or bolted to, mass concrete foundations.

Loading on these gantries includes contributions from:

- the self-weight of the structure and wires
- wire tension, taking account of temperature, deviation angles and eccentricities
- wind on the structure and wires
- ice on the structures and wires.

Since the loading on the existing gantries would change as a result of the proposed works, a structural assessment was required. Initially, assessments carried out by others in accordance with BS 5950-1[1] indicated that the structures would not be suitable for re-use due to high calculated utilisations. However, it was considered by Network Rail that these initial assessments were in some cases unduly conservative. Therefore, a review based on rigorous assessment was commissioned. The aim was to ascertain, as realistically as possible, the structural utilisations so that the number of structures requiring replacement could be accurately determined.

Methodology

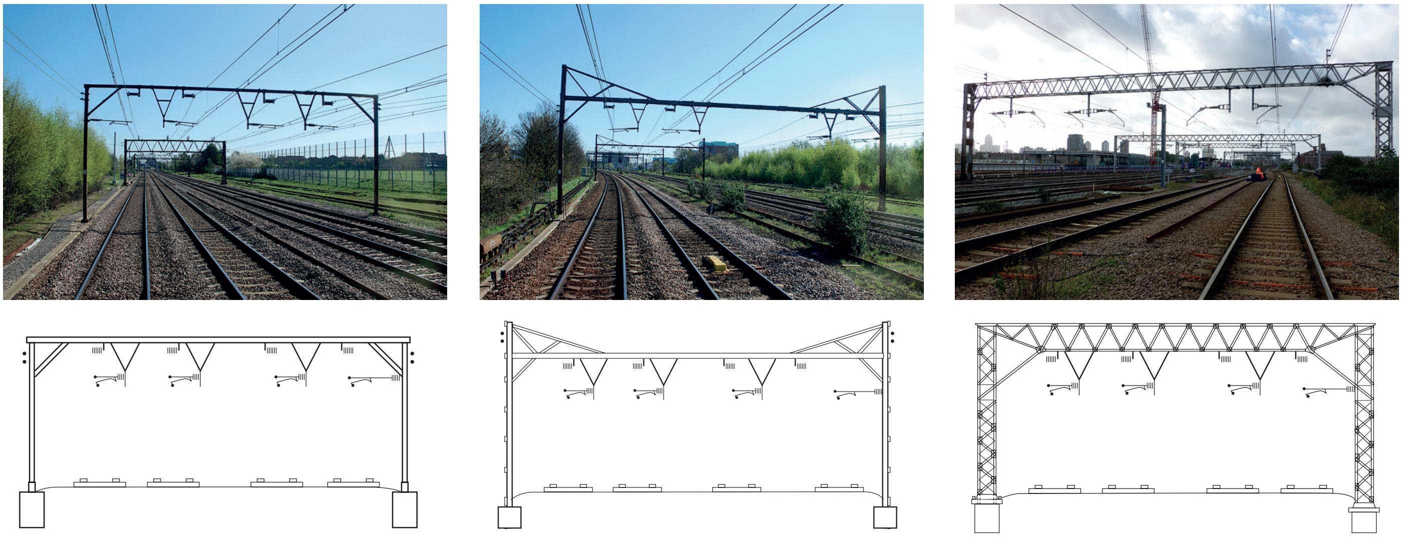
Strategy

The project required over 700 gantries to be assessed to a demanding timescale. Therefore, it was important to develop an efficient strategy for the work. It was considered important to eliminate unknowns and therefore remove conservatism as far as possible. In particular, the following aspects were considered:

Wind loading

Wind actions on structures located in cuttings can be significantly less than those in open country on embankments; therefore, site-specific wind loading was considered. Both along-track and across-track wind loading needed to be considered. Wind loads are applied to the gantry structure and the wires.

Figure 1
Types of OLE gantry



a) Single-span knee-braced portal (Great Eastern)

b) Single-span top-tie portal (Great Eastern)

c) Single-span lattice portal (Great Eastern)

d) Head span (Great Western)

e) Single-track cantilever (Great Western)

f) Two-track cantilever (Great Western)

Wire loading

As well as the new ATFs and earth wires, loads are applied by the contact and catenary wires. These wires can either be auto-tensioned or fixed termination. Auto-tensioned wires maintain the same tension regardless of temperature and this is therefore relatively well defined. Fixed-termination wires have tension that varies with temperature, typically increasing significantly at low temperature. (The assessment considered temperatures down to –18°C, which is considered conservative for the region under consideration). In a number of cases, gantries were assessed with both fixed-termination and auto-tensioned wires due to the phased replacement of older equipment.

Wire tensions are considered as external loads in the structural analysis, with any ‘guying effect’ conservatively ignored. Deviation of wires occurs at gantries due to track curvature or wire stagger on a straight track, and this is significant as it results in lateral loads. The registration arm of auto-tension equipment will move with temperature – the resulting position of wire loads and any associated eccentricity must be carefully modelled. Dynamic loads resulting from cable breakages were not considered.

"THE PROJECT REQUIRED OVER 700 GANTRIES TO BE ASSESSED TO A DEMANDING TIMESCALE"

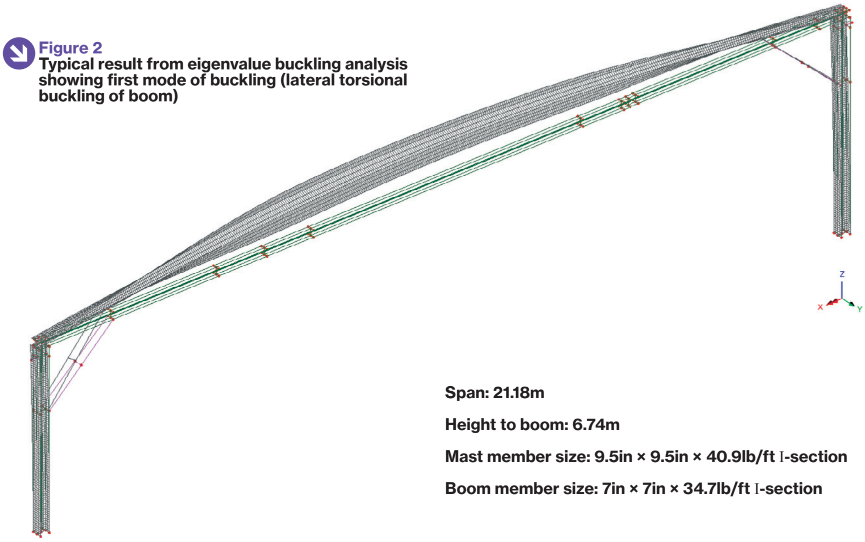


Figure 2
Typical result from eigenvalue buckling analysis showing first mode of buckling (lateral torsional buckling of boom)

Span: 21.18m

Height to boom: 6.74m

Mast member size: 9.5in × 9.5in × 40.9lb/ft I-section

Boom member size: 7in × 7in × 34.7lb/ft I-section

Ice loading
Ice loads are applied to both the structure itself and the wires and are assessed based on a 9.5mm radial thickness. The contact wire is assumed to be kept clear of ice by the passage of pantographs.

Condition
All of the structures were inspected by means of walk-through and high-level surveys to check their condition. Bearing in mind the age of the structures, the assessment assumed a default condition factor of 0.95 to cater for a moderate level of corrosion, etc. (The original treatment of the gantries was paint on the Great Eastern railway and galvanising on the Great Western.) Any observed defects adjudged to be more severe than this were explicitly considered in the assessment. It was assumed that adequate future maintenance would be undertaken to prevent any further deterioration.

Geometry
Record drawings existed for the majority of the gantry structures. Several structures have undergone modifications during their lifetime and this was checked and recorded as part of the site inspection. The number of items of OLE registered at the structures was also recorded and key dimensions and section sizes were checked.

Material testing
A limited number of material samples were taken on site from non-critical parts of the older Great Eastern gantries so that laboratory tests could be performed to verify the assumed steel strengths of the structures. For historic steelwork on the Great Eastern route, a yield strength of 230N/mm^2 was considered. For more recent steelwork on the Great Western route, yield strengths were based on the use of grade 50B (345N/mm^2) or grade 43A (275N/mm^2) steel, as noted on record drawings.

Datasheets and categorisation

Structure datasheets were prepared for each gantry with key dimensions (member sizes, boom height, across-track span, along-track span), wire heights and track alignment information, as well as inspection remarks and site photographs.

Each family of gantries was categorised into sub-families and the key data were

Figure 3
Typical result from non-linear analysis indicating onset of non-linearity at load factor of approx. 2.4, based on displacement (m)

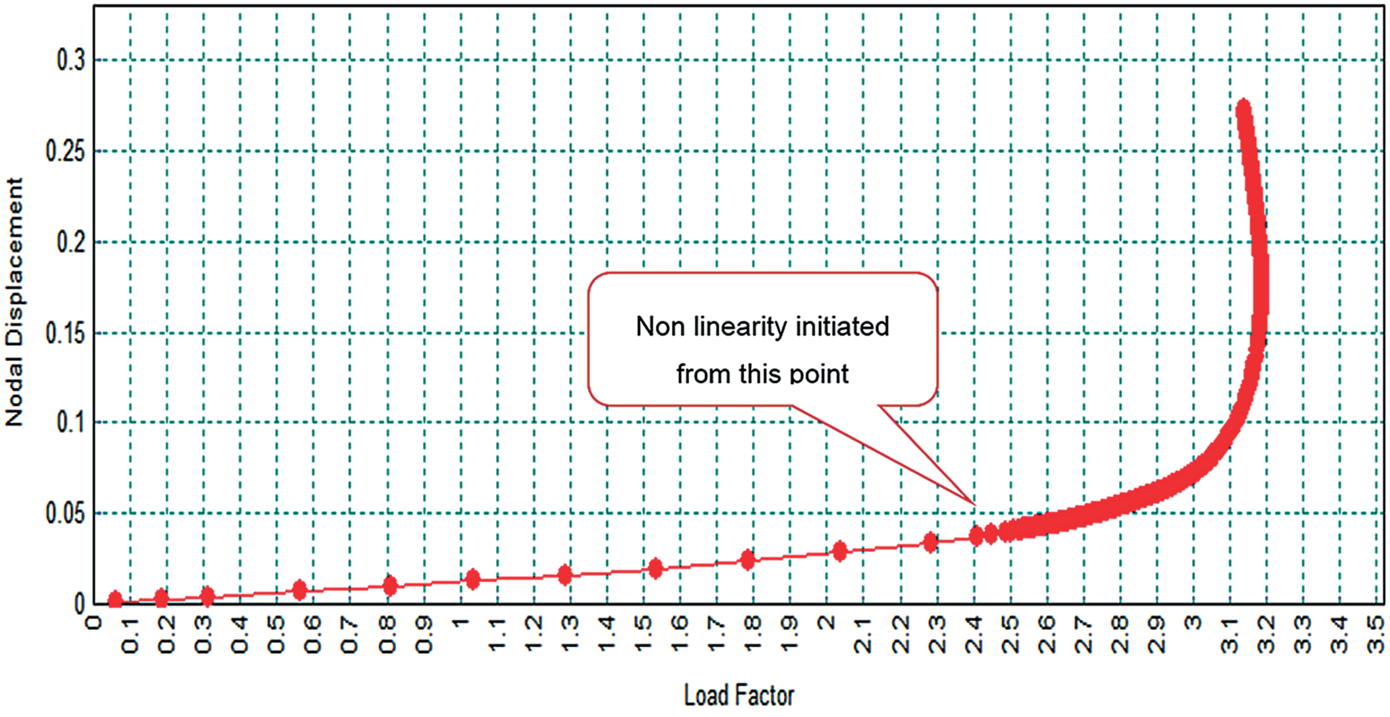
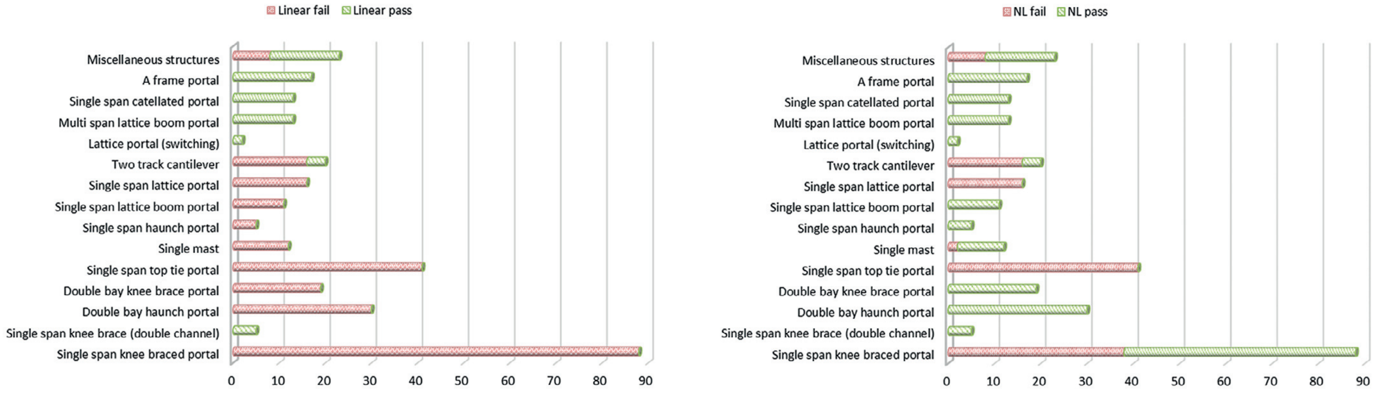


Figure 4
Summary of assessment results for main types of structure (Great Eastern)



a) Linear assessment results

b) Non-linear assessment results

tabulated so that the worst-case structure could be identified ('specific worst case' or SWC). Where it was unclear which structure would have the highest utilisation, an 'idealised worst case' (IWC) was used, derived using an envelope of variables. The assessment was carried out on the SWC or IWC structure and, if passed, the remainder of the sub-family was deemed also to pass.

When failures were found, the assessment progressively 'drilled down' into individual cases to study them in more detail.

Structural analysis

A staged approach to assessment analysis was taken. In the first instance, static analysis (including a check on connections) was considered, followed by non-linear analysis where this would give a better representation of the structure's behaviour. The conventional static analysis was an important first step in order to identify the potential problem areas within the structure. Serviceability deflections were also checked at this stage, although it was generally the ultimate limit state that was found to be critical.

The overall capacity of the slender gantry structures was in many cases found to be limited by the ability of the mast or boom members to resist lateral torsional buckling. This capacity is influenced by the structure's geometry, section properties, the shape of the bending moment diagram and the position of loads (in particular, their location relative to the shear centre of the member concerned, with destabilising loads having a particularly severe effect). In order to eliminate conservatism, rigorous analytical checks were proposed.

The approach adopted for the rigorous analysis was to model the gantry members with shell elements in the LUSAS finite-element program[2] (see Figure 2 for a typical model plot). A full second-order analysis incorporating material and geometric non-linearity was then performed. In the geometrically non-linear analysis, initial imperfections were introduced into the mesh by carrying out an eigenvalue buckling analysis and scaling the deformed shape for several critical buckling modes. The resulting geometry was then used as the starting point for the non-linear analyses, wherein loading was applied incrementally and, by subsequently plotting deformations against load factor, it was possible to determine the point at which divergent, non-linear structural behaviour occurs (Figure 3). A structure was considered to have adequate resistance to buckling if its behaviour was still within the linear zone when ultimate loading had been applied to the structure. Note that using this technique, all loads are subject to the same factor, which must account for uncertainty in the applied actions, material properties, analysis accuracy and structure condition.

A significant advantage of this approach is that the analysis models give direct results of the load factor, which can be related to the structural utilisation (where structural utilisation = 1 / load factor), without the requirement for post-processing of results and assessment of individual section capacities. This approach is in accordance with cl. 5.2.2(7)a) of EN 1993-1-1[3] which states: *'If second order effects in individual members and relevant member imperfections ... are totally accounted for in the global analysis of the structure, no individual stability check for the members ... is necessary'.*

> **"THE RIGOROUS NON-LINEAR ASSESSMENTS SHOWED A SIGNIFICANT IMPROVEMENT"**

The freedom from subsequent application of codified section checks removes any undue conservatism from the assessment process. This is a satisfactory approach for assessment, but would be cumbersome for design when member sizes need to be individually optimised. Since the initiation of the rigorous assessment work, a new Network Rail standard has been published with improved guidance on the design of OLE gantries[4].

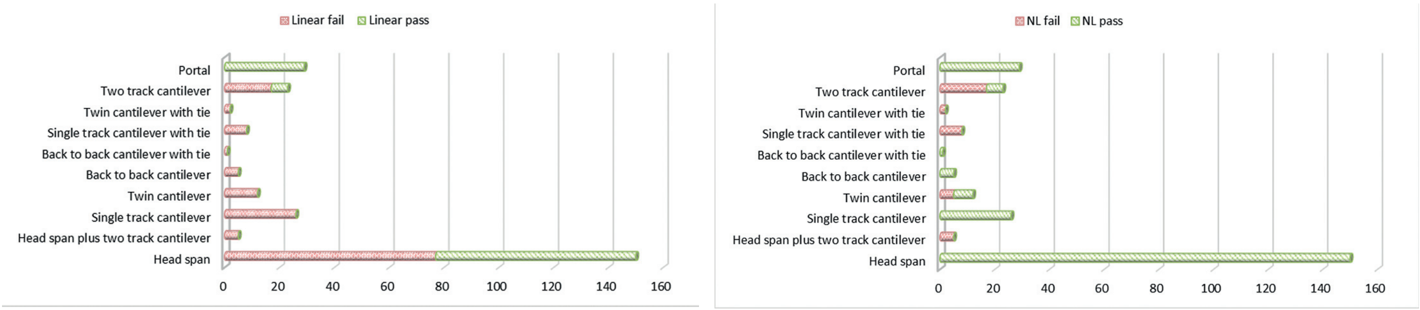
The assessment involved a repetitive process of model creation and analysis. Therefore, a Visual Basic script was developed to speed up the process of generating the analysis models for the gantries by deriving the loading and load combinations to be applied to them.

All assessments involving non-linear analysis were subject to independent checks using a different software package (ROBOT).

Assessment results and strengthening design

The assessment results are summarised graphically for the Great Eastern and Great Western structures in Figures 4 and 5 respectively. It can be seen that the rigorous non-linear assessments showed a significant improvement in terms of the number of gantries shown to be able to sustain the new TPS/OLE loading compared to the linear analysis. Overall, this number increased from 40% of the gantries considered to 75%.

Figure 5
Summary of assessment results for main types of structure (Great Western)



a) Linear assessment results **b) Non-linear assessment results**

> **"A COMMON DEFECT WAS CORROSION WHERE WATER TENDS TO COLLECT AT THE BASE OF THE MAST"**

Of the remaining structures, a number failed assessment due to condition. A common defect was corrosion where water tends to collect at the base of the mast. Single-span top-tie portals on the Great Eastern and two-track cantilevers on the Great Western were found to have a problem with connection capacity, which is why they failed even when assessed using non-linear analysis.

Where this had occurred, or mast base capacity was found to be inadequate, remedial measures were investigated. The solution proposed was a steel strengthening collar to be fixed around the base of the mast and bolted into the foundation. The space between the collar and the mast member was then infilled with concrete (Figure 6).


Figure 6
Collar strengthening at base of mast

With this and other strengthening measures that were identified, it was possible to incorporate the vast majority of the OLE gantries in the Crossrail works, with only a handful requiring complete replacement.

Conclusions

The work delivered significant cost and programme savings to the Crossrail project by demonstrating that the majority of the 700+ existing OLE gantries affected by the TPS upgrade works were suitable for re-use or could be strengthened. This positive outcome was achieved by removing undue conservatism in the gantry assessment, by reducing the number of unknowns (geometry, loading, condition, material strength) while maintaining a suitable level of safety. The use of rigorous non-linear analysis for the slender structures was proven to give particular benefits when considering susceptibility to lateral torsional buckling.

In order to streamline similar processes in the future, a parametric approach to generating analysis models and deriving loading has been developed.

Acknowledgement

The authors would like to thank Chuan Chu of Network Rail for his assistance in reviewing this paper.

Project team

Client: Network Rail
Structural engineer: BuroHappold
Geotechnical engineer: BuroHappold
Main contractor: Costain
Subcontractor: Keltbray

REFERENCES

►1) British Standards Institution (2001) ***BS 5950-1:2000 Structural use of steelwork in building. Code of practice for design. Rolled and welded sections***, **London: BSI**

►2) Finite Element Analysis Ltd (2018) ***LUSAS*** **[Online] Available at: www.lusas.com/ (Accessed: May 2018)**

►3) British Standards Institution (2005) ***BS EN 1993-1-1:2005+A1:2014 Eurocode 3. Design of steel structures. General rules and rules for buildings***, **London: BSI**

►4) Network Rail (2016) ***NR/L2/CIV/073: Design of Overhead Line Structures***, **London: Network Rail**

HAVE YOUR SAY

To comment on this article:
►email Verulam at tse@istructe.org
►tweet @IStructE #TheStructuralEngineer