

Institution: University of Warwick
Unit of Assessment: B15 General Engineering
Title of case study: European codes of practice for civil engineering structures (Case Study B15.5)
<p>1. Summary of the impact</p> <p>Research led by two members of the University of Warwick's School of Engineering strongly influenced the planning, drafting and technical content of nearly all of Eurocode 4, one of ten European civil engineering standards. Eurocode 4 covers composite structures made of steel and concrete. Since 2010 this standard has been in force in all countries of the European Union (EU) and the European Free Trade Area (EFTA). The Eurocodes are the only set of design rules for publicly-funded structures on land that satisfy national building regulations throughout the EU and EFTA. Their impact on structural engineering is wide-ranging and growing, the principles and methodology contained within these Eurocode 4 will be the basis of engineering design teaching for Chartered Engineers throughout the EU.</p>
<p>2. Underpinning research</p> <p>The rules of the EU and EFTA require that barriers to trade among member countries are removed, so it was necessary for the European Commission (EC) to generate a set of principles and rules for the design and construction of composite steel and concrete structures that would be accepted by each country and would satisfy their diverse national standards. To achieve this, research was needed to resolve differences in the meanings of units, symbols and so on and in the legal status of standards between nations. The new standards (Eurocodes) were based on the best available scientific evidence with uniform and consistent margins of safety and are designed to protect workers and the public and to save construction costs.</p> <p>In 1972, Professor Roger Johnson of Warwick's School of Engineering was invited to work on the new EU standards, initially as a member of the European Joint Committee for Composite Structures. He chaired the Composite Structures Sub-committee of CEN, the European Committee of Standardisation (1990-99), and led the project teams that prepared the relevant preliminary codes, ENV 1994-1-1 (1983-93) and ENV 1994-1-2 (1993-97) and also that for EN 1994-2 (Bridges, 1999-2005). His colleague, Professor David Anderson, led the EU project team that completed EN 1994-1-1 (Buildings, 1993-2004). Both are now Emeritus Professors at Warwick (Johnson, 1998, Anderson, 2003).</p> <p>The rules of Eurocode 4 were strongly influenced by research led by Johnson and Anderson. As conveners of the EU project teams they were actively engaged in all the technical aspects. This involved studying competing methods for design of composite structures (typically based on current national practice), calculations for evaluation and calibration [1], devising compromises and making proposals (often based on their own published research) that were adopted. The research was funded by various stakeholders (examples in Section 3). Their publications (examples in Section 3) had international impact and include the following:</p> <ul style="list-style-type: none"> • ductility is required in composite joints to enable redistribution of moment which may be provided through yielding of the slab reinforcement and slip of the shear connection. As the reinforcement may eventually fracture, a calculation method is needed to determine the rotation corresponding to this failure mode. This research developed such a method and comparisons with test results show good agreement. The proposed model can also be used to predict rotation capacity limited by slip due to partial shear connection [2]. • methods for analysis and design for distortional lateral buckling of beams, shear connection and bending resistance in composite slabs [3], partial shear connection in beams, tension stiffening in cracked concrete [4], and interaction between bending and shear in beams; • the resistance to longitudinal shear by stud shear connectors depends on over 20 parameters. This research developed improved methods of testing and provided validated mechanical models of stud shear connectors; statistical analyses of results [1]; and • how to use the English language with a precision that was accepted by experts in all countries involved, and could be widely translated without ambiguity [5]. <ul style="list-style-type: none"> • Shear connectors and transverse shear in composite beams and slabs; • Connections in composite frames;

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- Redistribution of moments in continuous composite beams;
- Vertical shear in composite beams; and
- Biaxial bending of composite columns

3. References to the research

The outcome is in the codes themselves and the published Designers' Guides [6, 7] which refer to over 70 publications by authors from the School of Engineering, a selection provided below. All parts of Eurocode 4 were completed and published as British Standards by 2005 and were used in parallel with National Standards until the latter became unavailable for new public works projects in 2010.

Publications:

1. **Johnson R.P.**, "Calibration of resistance of stud shear connectors in troughs of profiled sheeting". *Proc. Instn Civ. Engrs, Struct. and Bldgs*, 161(3) 117-126. (2008) DOI: 10.1680/stbu.2008.161.3.117
2. **Anderson, D.**, Aribert, J.-M., Bode, H. and Kronenberger, H.-J., "Design rotation capacity of composite joints", *The Structural Engineer* 78(6) 25-29. (2000)
<http://www.istructe.org/webtest/files/f9/f9021aa8-b08b-4bbf-93b4-c5289a2c1a33.pdf>
3. **Johnson, R.P.**, "Prediction of shear resistance of headed studs in troughs of profiled sheeting". *In Composite Construction in Steel and Concrete VI*, ed. R.T. Leon et al, 1-13, Amer. Soc. Civ. Engrs, New York. (2011) DOI: 10.1061/41142(396)1
4. **Johnson R.P.**, "Control of cracking in composite bridge decks in regions of biaxial tension". *Stahlbau*, 80(12) 880-884. (2011) DOI: 10.1002/stab.201101497
5. **Johnson R.P.**, "Eurocodes, 1970-2010: why 40 years?", *Proc. Instn Civ. Engrs, Struct. and Bldgs* 162(6) 371-9. (2009) DOI: 10.1680/stbu.2009.162.6.371
6. Hendy C.R. and **Johnson R.P.**, "Designers' Guide to EN 1994-2: Design of composite steel and concrete structures; General rules and rules for bridges", pp. x, 206. *Thomas Telford*. (2006) ISBN: 9780727731616
7. **Johnson, R.P.**, "Designers' Guide to EN 1994-1-1: Design of composite steel and concrete structures; General rules and rules for buildings", 2nd ed., pp. xiii, 256. *Thomas Telford*, London. (2012) ISBN: 9780727731517

Grants/awards:

Grants totalling £197,500 were received in the period 1993-1998, including the following:

PI: R.P. Johnson; Support for work on Eurocode 4; Steel Construction Institute; 6 awards from February 1993 to July 1996; total £40,449.

PI: R.P. Johnson; Push Tests on Stud Shear Connectors; UK Department of the Environment, 01-Jan-1994 to 02-Jul-1995; £27,245;

PI: R.P. Johnson; Eurocodes; EU Directorate General III; 01-Sep-1995 to 01-Mar-1998; £43,235.

PI: R.P. Johnson; Review of EC4 Part 2 - Steel/Concrete Composite Bridges; UK Department of Transport; 20-May-1995 to 28-Feb-1997; £83,825;

PI: R.P. Johnson Eurocode 4 Part 2 - Composite Bridges; Railtrack; 01-Dec-1996 to 30-Jun-1997; £18,000.

The election of both Johnson (1986) and Anderson (2004) to the Fellowship of the Royal Academy of Engineering (RAE), and the award to Johnson of the Gold medal of the Institution of Structural Engineers in 2006 provides evidence of the quality of their research and the impact of their work on Eurocodes. Anderson's RAE citation specifically referred to his work on European codes for composite structures.

4. Details of the impact The underpinning research and the completion of Eurocode 4 have had significant impact through the mandatory application as policy by the EC and all the EU member countries with changes to legislation, regulations and guidelines. The impact from policy is also demonstrated through the effect and benefits to practitioners and professionals in the construction industry.

Policy:

Civil engineering structures are designed by chartered engineers working for a client, using methods that must ensure the functionality, safety and durability of the structure. The Eurocodes are the only set of design rules for publicly-funded structures that satisfy national building regulations (and similar client-based rules for structures such as road and rail bridges) in all countries of the EU and EFTA. There are ten Eurocodes (over 3000 pages in total). Johnson and Anderson had prime responsibility for the drafting of Eurocode 4 (save for its section on fire resistance). The Eurocodes are the *first* set of design rules for civil engineering structures to achieve three-way harmonisation: across types of structure (such as buildings, bridges, towers, masts, foundations); among many nations; and across a range of structural materials (such as steel, concrete, timber, light alloys and soils).

Reach and economic impacts on the EU:

Some of the main benefits of the Eurocodes (detailed on the EU DG 'Enterprise and Industry' website [8]) are more uniform levels of building safety across Europe; a common understanding of the design of structures between owners, operators, users, designers, contractors and manufacturers of construction products; and a common and transparent basis for fair competition in the European construction market. The EC also states [8] four economic impacts, these include the fact that firms, particularly SMEs, have improved access to 27 countries and 500 million consumers in Europe. A report published by the EC also highlights the impact, providing examples of the application of Eurocode 4 such as the high-speed rail line in Spain [9] (this source cites work by Johnson).

The Head of Bridge Design and Technology for consultancy Atkins is responsible for the technical leadership of their 650 bridge engineers around the world. He comments [10] that the significant standard of the Eurocodes has reached further than just EU public constructions: "Eurocodes have given us a common language and common rules that we didn't have before, covering: all our European operations (and Middle East, Hong Kong, India); and the interface between civil engineering and building...allowed us to develop better shared training and software, mobility of staff...the net effect is some efficiency in delivery". This efficiency of working and the ease of working across Europe is also corroborated by consulting engineers Arup [11] "...even in countries where we do not have a presence".

Examples:

The timescale of the development of Eurocodes is long (it took over 30 years to develop them). Design and construction takes several years, so few structures designed to Eurocodes have been completed by 2013. However, the draft Eurocodes influenced the basis of structural design of a few international projects in the 1990s. Examples are the bridge over the Øresund between Denmark and Sweden (2000), and a novel structure for the Millennium Tower in Vienna (2000).

Further examples of the direct application and impact of Eurocode 4 are demonstrated by the company Acciona, a leader in infrastructure, who consulted on project design for the bridges in the Spanish high speed rail system. Acciona's Director of Steel Structures [12] (and a member of the committee for the Spanish national standards) corroborates the significance of Johnson's work on the Eurocodes and also how Spain incorporated early versions of Eurocode 4 (prior to the mandatory 2010 incorporation) into many projects. He highlighted eleven, including the construction of the Barcelona Design Centre in 2011, the refurbishment of the National Archaeological Museum in Madrid in 2009 and the building of many bridges and viaducts (from 2006 to 2012). He states [12]: "Designs were also carried out in Brazil and Sweden, for road and railway bridges, and all of them are based on Eurocodes 4 clauses. The content of Eurocodes 4 means a guaranteed design for all of the countries in which the composite steel and concrete construction is not developed as in European countries".

Significance:

Emeritus Professor, former Head of the Department of Civil and Environmental Engineering at Imperial College, who was for more than 10 years chairman of the BSI Committee responsible for BS5950 and for UK input into EC3, is a past chairman of IABSE's technical committee responsible for oversight of all the Association's technical activities and a past Deputy Chairman of the Council

of the Steel Construction Institute [13] supports the importance and impact of Warwick's research. He writes the introduction of Eurocodes "represents the largest and most significant change ever presented to UK structural designers...The monetary value is huge; construction typically accounts for about 10% of GDP in developed countries. The number of engineers affected is huge; the UK has tens of thousands of engineers engaged on structural works...There is no doubt that in the specific area of composite construction the contribution by Warwick at both the fundamental level of providing the essential understanding of behaviour and in then translating that into workable design procedures (a task that I regard as every bit as intellectually challenging as conducting the original research) is the single most substantial of all the contributing parties".

Professional and practitioner impacts:

Early impacts on the mandatory adoption of Eurocodes affected the software industry; the training of engineers by the leading structural consultants, the publishers of explanatory material [1, 6], and experts worldwide tasked with revising their national codes. In response to the demand for understanding the application, the British Standards Institution (BSI) set up 'Eurocodes Plus' a software/interactive tool utilised by consultants and structural engineers [14]. The BSI also provides courses and training to support the UK industry.

The use of Eurocodes also involves radical changes in the methods of analysis and design used for major projects by structural engineers, who needed new software. The company Bestech, a leading UK supplier of software for the design and code verification of bridges, has incorporated all of the Eurocodes into their products. Its Director specifically quotes the significance of research at Warwick's School of Engineering and the role of Johnson and Anderson in disseminating this research to practitioners and software developers supporting the industry [15]. The Eurocodes are influencing national standards/codes in many countries. During the REF period Johnson and Anderson have been invited to run courses on Eurocode 4 for research staff and consultants in Australia, South Africa, Canada, Malaysia, Singapore, Iceland, Israel, Qatar and the USA. They have also run lectures and been invited to give conference presentations in other countries. Australia, South Africa and Canada are studying the Eurocodes as the potential basis for revision of their national codes. Many smaller countries that use British Standards are now adopting the Eurocodes.

5. Sources to corroborate the impact

8. EU DG 'Enterprise and Industry' website: <http://eurocodes.jrc.ec.europa.eu/home.php>

9. EU Report 'Bridge Design to Eurocodes' providing examples of the application of Eurocode 4 such as the high-speed rail line in Spain [9] (this source cites work by Johnson p 128, 173).
http://eurocodes.jrc.ec.europa.eu/doc/1110_WS_EC2/report/Bridge_Design-Eurocodes-Worked_examples-main_only.pdf

10. Letter from the Head of Bridge Design and Technology, Highways and Transportation, Atkins.

11. Letter from an Associate Director at Arup, consulting engineers, and Chair of the relevant committee of BSI (B/525/4).

12. Letter from the Director, Steel Structures Department, ACCIONA Infraestructuras, S.A. (Corporation)

13. Letter from Emeritus Professor, former Head of the Department of Civil and Environmental Engineering at Imperial College, who was for more than 10 years chairman of the BSI Committee responsible for BS5950 and for UK input into EC3, is a past chairman of IABSE's technical committee responsible for oversight of all the Association's technical activities and a past Deputy Chairman of the Council of the Steel Construction Institute

14. BSI 'Eurocodes Plus' software/interactive tool <http://shop.bsigroup.com/eurocodes-plus/>

15. Letter from the Director of Bestech Systems Limited.