Alfredo Boracchini

Design and Analysis of Connections in Steel Structures

Fundamentals and Examples

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Detail of a Moment Connection
in a Composite Building Structure
("InterPuls spa" Building, Reggio Emilia, Italy)
Photo: Alfredo Boracchini

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To my mom Alda

Preface

Structural Steel Connection Design is an engineering manual directed toward the engineering audience. The first section provides an introduction to key concepts, then progresses to provide a more in-depth description for the design of structural steel connections.

A correct approach to connection design is fundamental in order to have a safe and economically sound building. Therefore, this book will attempt to explain how to set up connections within the main calculation model, choose the types of connections, check them (limit states to be considered), and utilize everything in practice.

The focal point of the book is not to closely follow and explain one specific standard; rather the aim is to treat connections generally speaking and to understand the main concepts and how to apply them. This means that, even though Eurocode (EC) and the American Institute of Steel Construction (AISC) are the most referenced standards, other international norms will be mentioned and discussed. This helps to understand that connection design is not an exact science and that numerous approaches can be viable.

Type by type, connection by connection, detailed examples will be provided to help perform a full analysis for each limit state.

An excellent software tool (SCS – Steel Connection Studio) will be illustrated and used as an aid to assist in the comprehension of connection design. The software can be downloaded for free at www.steelconnectionstudio.com or at www.scs.pe and can be installed as a demo (trial) version (limitations about printing, saving, member sizes, and reporting), see "Software Downloads and its Limitations" (page xxiv). A professional full version can also be purchased online but the demo version is enough to reproduce the examples in the book.

The book will also try to deliver some practical suggestions for the professional engineer: how to talk about bracings to the architect, how to interact with fabricators showing an understanding of erection and fabrication, and much more.

Many countries have a deeper engineering culture about concrete structures than steel structures. This manual therefore aims to illustrate to engineers that do not design steel structures daily, some concepts that will facilitate and make their design of connections for steel structures more efficient. This will be done using a practical, rather than a theoretical, approach.

Design of steel structures can become tricky when it is about stability (buckling) and joints: this second fundamental aspect of steel constructions, which is crucial for economic performance, will be examined in detail.

The text, figures, charts, formulas, and examples have been prepared and reported with maximum care in order to help the engineer better understand and set up his or her own calculations for structural steel connections. However, it is possible that the book contains errors and omissions, and therefore readers are encouraged to have standards at hand as their primary reference. No responsibility is accepted and taken for the application of concepts explained in the manual: the engineer must prepare and perform any analysis and design under his or her complete competence, responsibility, and liability.

For a list of errors and omissions found in the book and their corrections, please check www.steeldesign.info.

Finally, please use www.steeldesign.info to send comments, suggestions, criticisms, and opinions. The author thanks you in advance.

April 2018

Alfredo Boracchini
Reggio Emilia

About the Author

Alfredo Boracchini is a Professional Engineer in Italy, Canada, and some states of the United States. His professional experience is mainly in steel structures that he has designed and calculated for many applications and in various parts of the world. He is an active member in some international steel associations and the owner of an engineering firm with offices in Europe, Asia, and America. This allowed him to collect extensive international experience in the field of steel connection design that he shares in this manuscript with other engineers interested in this field.

Contents

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The author is grateful to Giovanna Zanardi for her assiduous support and to Renzo Mazzali for his precious advice.

I also wish to express my gratitude to Antonella, Alda, Emma, Irma, Vera, and Lea for their love and for sharing daily with me, sometimes in spite of themselves, my passion for structural engineering.

List of Abbreviations

AISC	American Institute of Steel Construction
ASD	allowable stress design
AWS	American Welding Society
BS	British Standards
CG	center of gravity
EC	Eurocode
EN	European Standard
DIN	German Institute for Standardization
ECCS	European Convention for Constructional Steelwork
FCAW	flux-cored arc welding
FEA	finite element analysis
FEM	finite element method
GMAW	gas metal arc welding
HSS	hollow structural steel
ISO	International Organization for Standardization
KISS	keep it simple stupid
LRFD	load and resistance factor design
NDP	nationally determined parameter
NTC	Italian Standard for Constructions
OSHA	Occupational Safety and Health Administration
PL	preload
PR	partially restrained
RCSC	Research Council on Structural Connections
SAW	submerged arc welding
SCS	Steel Connection Studio
SMAW	shielded metal arc welding
TOS	top of steel
UFM	uniform force method

Software Download and its Limitations

The engineer can use the book to get familiar with SCS – Steel Connection Studio, a fantastic software tool that can be used in the design of steel connections. The software (which can be downloaded from www.steelconnectionstudio.com or www.scs.pe) works in a demo version with the following limitations:

- Only 90 consecutive days of usage are allowed after installation. Providing the code *Ej8Z4pn1* the demo version can be extended with no time limitation. Please send an email to info@scs.pe if you are interested in this offer.
- File saves are not possible.
- Commercial and academic usage is not possible.
- Maximum dimensions of members are 254 mm/10 in. in width and 361 mm/14.2 in. in depth. The sketch cannot be printed.
- The word *demo* is watermarked in the sketch.
- The maximum number of reports that can be generated is 25.

For videos, tutorials, validation examples, the manual, and additional (commercial too) information, please visit www.steelconnectionstudio.com or www.scs.pe.

1

Fundamental Concepts of Joints in Design of Steel Structures

Regarding joints, the first fundamental concept the engineer must be clear about when he or she starts to design is which connections will develop moment resistance and which can be executed as simple pin joints. To do this, it is necessary to clarify the lateral load resisting system.

1.1 Pin Connections and Moment Resisting Connections

1.1.1 Safety, Performance, and Costs

Steel structures should be safe, able to perform, and be cost-effective.

They must be safe because they act as canopies, mezzanines, buildings, skyscrapers, bridges, and much more that give shelter, protect, and be welcoming to men and women. A structural collapse is extremely dangerous and likely to cause severe harm to anyone in the surrounding area.

Structures must also effectively serve their commercial purpose while efficiently and comfortably (for the users) maintaining their design features over time. These are the basic notions of serviceability limit state design specifying that, just as a nonlimiting example, deformations will not damage secondary structures or that excessive vibrations will not make users uncomfortable.

Poor performance might also decrease the structure's value and harm the property owner.

Simultaneously, the market logic requires that the structural system be economically sound and cost-effective when compared to alternatives using different materials and design. Being economically sound is a complex matter that must take into account many factors in the building design. However, the engineer must make the structure as cost-effective as possible without compromising safety and performance. The service and expertise that engineers are expected to deliver should include reducing costs while maintaining high standards of functionality and protection.

For the principles stated, the design of connections is a focal point and it must be well defined in the engineer's mind from the commencement of the project.

Design and Analysis of Connections in Steel Structures: Fundamentals and Examples,
First Edition. Alfredo Boracchini.

1.1.2 Lateral Load Resisting System

The choice of connections is related to the choice of the lateral load resisting system.

Taking a closer look at this key point, we consider these initial hypotheses: that the structure geometry is defined, that steel will be used as structural material, and that the design loads are provided. This means that the engineer can set up the analysis model with the finite element software available. However, before building the model wireframe, the engineer must have a clear vision of the lateral resisting system(s). This choice influences costs and architectural restraints.

Lateral load resisting systems can be diverse and variously combined among themselves. Each horizontal direction can have its own system, one that may be different from the other direction.

The basic lateral resisting systems (Figure 1.1) are as follows:

- Braces (bracings)
- Moment connections (portals)
- Base rigid restraints (cantilever columns or inverted pendulum)
- Connection to an existing structure or another ad hoc structure built with different materials (say a concrete staircase, masonry or concrete walls, etc.).

The structural engineer attentive to fabrication logics usually tries to adopt bracings as this will deliver maximum cost performance. The main advantages of using braces are as follows:

- The structure is easily sized against horizontal forces (mainly wind and earthquakes) allowing less weight for beams and, most of all, columns (braces take care of lateral forces and the column can work only in compression).
- Connections can roughly be just in shear or axial action and so are light and economic.
- Lateral deflection control is excellent.
- Seismic response is good (given that the necessary detailing is provided).

At the same time bracing has some disadvantages:

- It laterally obstructs the transit, limiting windows or gates.
- The architect or the owner might not like it for esthetic reasons.

This last problem might be solved by "highlighting" the braces and assigning architectural importance to them. Some famous examples can be found, such as landmark skyscrapers (Figure 1.2) and more "ordinary" buildings (Figure 1.3), where the architect was able to create an interesting contrast with materials that nicely emphasize the braces.

The problem of transit obstruction is usually bypassed by choosing one specific bay for braces, if possible. This is done either in the middle or at the end of the building system. Horizontal braces are implemented to bring forces to the localized braces. (This book does not discuss the layout of horizontal braces. Rather it discusses one of their main functions, beyond limiting flexural torsional buckling of beams, that is, to connect unbraced bays to braced ones.)

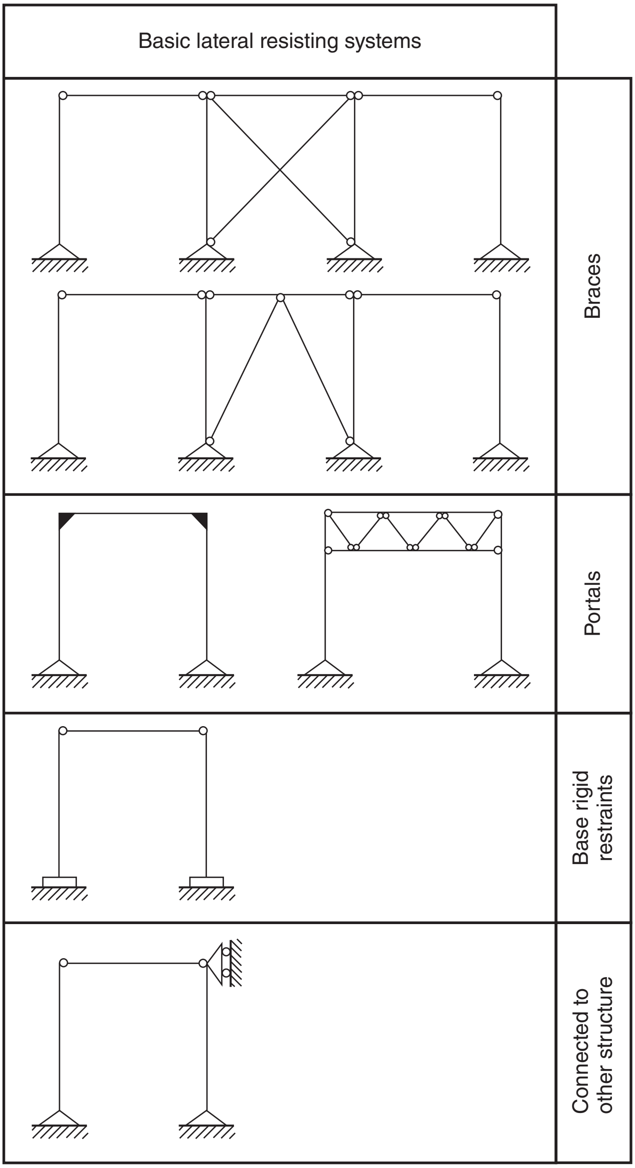

Figure 1.1 Lateral load resisting systems.

Another method to limit the obstruction in the space occupied by the braces is to adapt their geometry to the challenges of architectural restraints using different schemes and shapes (V, inverted-V, X, K, Y, and more).

Having given the many advantages of using braces and the importance of informing the owner and the other players about this solution in order to have it approved, in many situations it is not possible to use braces, especially in both directions. As a consequence, it is necessary to use portals or base rigid

Figure 1.2 Braces emphasized esthetically in the John Hancock Tower of Chicago. Source: From Wikipedia; photo courtesy of "Akadavid", 2008.

connections or a combination of them, if not different additional schemes such as shear steel walls or other concrete or composite systems that are outside the scope of this book.

The main advantage of using portals and rigid bases is what made braces undesirable; that is, there are no obstacles in fully exploiting all the space of the bays. In addition, moment resisting systems (by the way, it is not trivial to underline that a system made by trusses and columns is a specific case of a portal) have the following advantages:

- Possible savings (at the expense of the dimension and cost of the columns) in beam depth since the moment connection allows a better exploitation of the beam strength along the full length.
- A more "convincing" look of the columns that, being heavier, seem safer.
- Pin (hinge) connections at the base, then savings in foundation work (larger even compared to braces, which could give an uplift and require more expensive tension details and some "ballasting" of the plinths).
- Reasonable seismic resistance (if the necessary detailing is followed).

Figure 1.3 Valorization of internal braces (InterPuls, Reggio Emilia, Italy).

Disadvantages of portals might be the following:

- Moment connections are required and they are usually complex and more expensive.
- Additional encumbrance may be provided by the beam-to-column connection (net height at the eaves is impacted and this could make it mandatory to raise the whole structure); also, the obstruction given by trusses is similarly and evidently large.
- On average, the weight per unit of area will worsen.
- Lateral deflections should be checked carefully.
- Buckling length of columns worsens.

A lateral resisting system having the columns rigidly connected to the base may have the following benefits:

- No obstructed bays, as already mentioned.
- Larger columns inspiring more confidence in the safety of the building.

The following are some of the disadvantages:

- Expensive foundation work required: large plinths, piles likely mandatory
- Lateral deflections to check (but usually better than portals)
- More material (steel) necessary to build the structure
- Longer buckling length of columns
- Poor seismic performance (for example, the American Society of Civil Engineers (ASCE) basically bans this system for buildings if the area is highly seismic (see Ref. [1] for more precise information)).

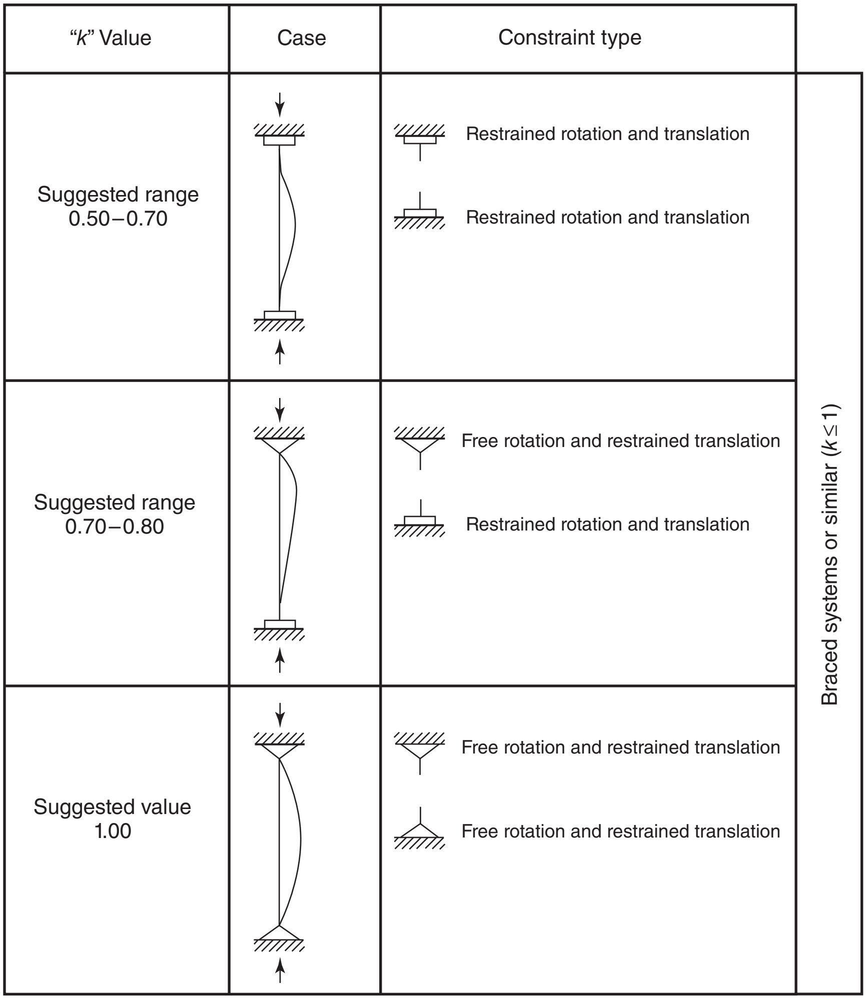

Figure 1.4 Buckling length coefficients (effective length factors) for braced systems.

Sometimes, to solve the problems of lateral deflections and column buckling length (see Figures 1.4 and 1.5 for reference values), both systems are contemporarily adopted.

As Figure 1.5 shows, the buckling length of columns is two times the physical length in each system when taken by itself, but it goes back to almost unity (braced systems have 1) when used in a combined system.

Every situation is different and braces are not always the best option. For example, if the structure has large bays (beyond 20 m, or 60 ft) and that direction already uses trusses in its architectural layout, it is already a moment resisting system that can be exploited as a lateral resisting system. Braces can be used only in the orthogonal direction, effectively restraining the weak side of the columns.