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MEICON

Minimising Energy in Construction

Origin of 100 psf

Report

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"In every building, the floor shall be of sufficient strength to bear the weight to be imposed upon them, exclusive in all cases of the weight of material used in their construction"

The Laws of New York State 1860 [1]

"It was found that live loads assumed in designing many types of buildings were largely matters of tradition and had scant scientific basis."

Woolson et al. (1925) [2]

"Historically buildings have been designed for far higher loading than regulations require and beyond what they experience in practice. This over specification has become the norm based on perception in the market place that this provides a degree of flexibility."

BCO Guide to Specification 2014 [3]

"Unrealistic design loads should not be used when it is impossible to generate that load or when, with a little forethought and simple guidelines on activity, high loading can be avoided."

Hume and Miller (2015) [4]

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Chapter 1: Office floor loading

1 Introduction

As part of the research project "Minimising Energy in Construction" (MEICON) the origins of floor live load values for office buildings were investigated. This report examines how loading values for office buildings have evolved over the last two centuries, considering both values recommended by design codes, and values used in practice.

A primary driver for this report lies in the fact that historical values for imposed loading in offices of 100 pounds per square foot (psf) or 4.80kN/m^2, first introduced in the 1800s [5], are still often used in the design of new office buildings, despite design codes requirements being closer to 2.5 kN/m^2 (52.2 psf) [6]. Use of higher than required design loading and the use of design loading far in excess of real loads, might lead to significant material inefficiencies.

The aim of this report is to help architects, structural engineers, clients, quantity surveyors and letting agents understand design live load values.

Figure 1: Barrels in warehouse, 4.90 kN/m^2 = 102 psf (source: OHA[1], 19th century)

Figure 2: Office loading of 4.6 kN/m^2 (96.1 psf) or 29 people over 4.5 m^2 [7]

Figure 3: Office loading of 2.8 kN/m^2 (58.5 psf) 29 people over 7.5 m^2 [7]

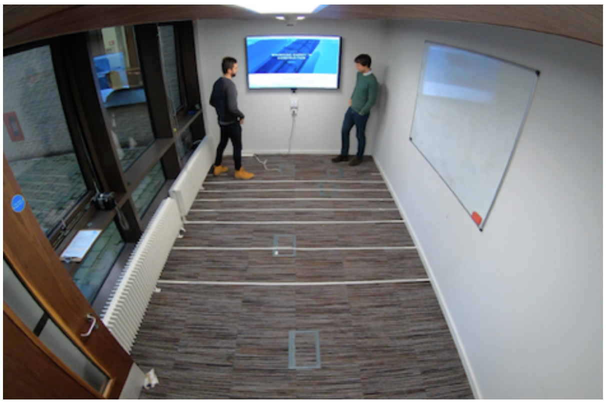


Figure 4: Office loading at BCO occupancy density of 7.5m^2 per person (0.01kN/m^2, 2.1psf) [7]

[1] Salt Played Role in War of 1812, https://www.syracusenewtimes.com/salt-played-role-in-war-of-1812/

2 Floor loading

2.1 Code requirements

Design codes classify actions[2] on buildings by their variation in time. *Permanent actions* such as those caused by self-weight tend not to change during the operational life of a structure. *Variable* and *accidental actions* such as those caused by wind, snow, and people, vary continuously [6, 8].

It has historically been difficult to obtain reliable data on the actual floor loading on structures, and as a result imposed loads specified in BS EN 1991-1-1 [6] are nominal values, derived by consensus amongst experts at a level considered to represent conservatively the maximum load likely to be experienced by a structure during its design life with an acceptably low probability of being exceeded [9]. For offices designed in Europe, BS EN 1991-1-1 [6] proposes imposed load values of between 2.0 and 3.0 kN/m^2. This is in line with values used around the world: analysis of structural design codes for 64 countries found design imposed loads for offices to be, on average, 2.38 kN/m^2 [10].

Design codes require loading of 2.0-3.0kN/m^2 for offices, which suggests a measure of uncertainty in what the loading values should be.

2.2 Design practice

Despite the fact that the office space is rarely loaded with heavy equipment, office buildings are often designed for much higher loads than required by design codes. Examining 95 office buildings competed in the last 20 years and located in the UK, US and Canada (6.3M square metres in total), we found an area weighted average live load of 3.57 kN/m^2 with an average allowance for partitions of 1.06 kN/m^2 [11] was used in design. Half of the analysed floor space was designed for 4.50 kN/m^2 (3.15 million m^2) and 10% for 5.00 kN/m^2 or more. These values are close to 100 psf (4.80kN/m^2)

2.2.1 Origins of 100 pounds per square foot.

A value for imposed loading of floors of one hundred pounds per square foot appeared in 1881 for dwellings [12], in 1884 for “storage of grain” [13] and in 1891 for “rooms for light mechanical purposes” [14]. This load has since been adopted for office space and is still used today. From the analysis we have undertaken, we consider the origin of 100psf to come from the storage of salt in American Standard Barrels (Figure 1). It is worth noting that 100 psf is the same as half a tonne for every square meter in the building, or 6.5 average people on every square metre, or a packed Tube Train during rush hour. However, it may not accurately reflect real floor loading in an office.

The evidence suggests that floor loadings for design are routinely specified above what is required by design codes.

2.2.2 Limit state design

Limit state design is a philosophy under which structures are designed such that the probability that a number of performance criteria are exceeded is deemed to be acceptably

[2] Actions can be “direct” – for example a point load applied to the structure, or “indirect” – for example deformation caused by temperature changes.

small during the required functional lifetime of the structure. When a structure, or element within a structure, ceases to satisfy one or more of these performance criteria it is deemed to have exceeded a *limit state* and thus now fails to fulfil satisfactorily the design requirements. The ultimate limit states are those which concern “the safety of people and/or the safety of the structure” [15]. The serviceability limit states are those which concern the “functioning of the structure or structural members under normal use, the comfort of people, the appearance the construction works” [15]. The requirements of limit state design may be met by design directly based on probabilistic methods (Annex C of EN1990 [15]), or by the partial factor method. The partial factor method is understood to be by far the dominant method used in practice.

Using the partial factor method, the designer must verify that limit states are not exceeded. This requirement is summarised in Eq. (1) and Eq. (2):

$$E_d \leq R_d \quad (1)$$

Where E_d is the design value of the effects of actions and R_d is the design value of the corresponding resistance

$$E_d \leq C_d \quad (2)$$

Where E_d is the design value of the effects of actions specified in the serviceability criterion, and C_d is the limiting design value of the relevant serviceability criterion

2.2.3 Actions

An action can be a *direct* force (load) applied to the structure (e.g. dead loads (self-weight) and live loads (i.e. variable loads such as traffic, pedestrian loading)) or an *indirect* action such as an imposed deformation or acceleration caused, for example, by temperature changes, settlement or earthquakes. They are normally classified according to their variation in time (permanent, variable, or accidental), which gives us some hint as to how they are modelled. In the Eurocodes, a “characteristic” value of an action is the main representative value. For permanent actions, a single value may be used if the variability of the permanent action is small over the working life of the structure. In general, there is much greater certainty as to the value of permanent actions such as self-weight, since these are directly measurable on each structure and are normally defined by the designer.

For variable actions, the characteristic value according EN 1990 [8] to corresponds to either:

a) An upper value with an intended probability of not being exceeded, or a lower value with an intended probability of being achieved, during a specific reference period, or:
b) A nominal value, which may be specified in cases where a statistical distribution is not known.

In practice it is very difficult to obtain reliable data on the actual loading on structures. As a result, loads specified in design codes are usually derived by consensus amongst experts at a level considered to represent conservatively the maximum load likely to be experienced by a structure during its design life with an acceptably low probability of being exceeded. For example BS EN 1991-1-1 [16] gives imposed loads for office floors as nominal values.

Further discussion on uncertainty in design, and the use of partial safety factors, is given in the MEICON report on “Uncertainty”, available online at www.meicon.net.

2.3 Real floor loading

It would be tempting to assume that loading codes are based around what really occurs in buildings, perhaps being based around measurement. Research to assess actual live loads in the buildings has been conducted for more than one hundred years. Key findings from these various studies are summarised in Table 1. The largest recorded floor load across all studies was 1.90kN/m^2 (from a study in 1893) and where for studies where an average loading was reported the average of these was 0.63kN/m^2.

The *Report of Building Code Committee* published in 1925 stated:

> *"(…) live loads assumed in designing many types of buildings were largely matters of tradition and had scant scientific basis" [2]*

Other quotes of interest include:

> *"Historically buildings have been designed for far higher loading than regulations require and beyond what they experience in practice. This over specification has become the norm based on perception in the market place that this provides a degree of flexibility." [3]*

> *"Unrealistic design loads should not be used when it is impossible to generate that load or when, with a little forethought and simple guidelines on activity, high loading can be avoided." [4]*

Table 1: Floor loading in office buildings.

Year	Source	Building typology	Area (m^2)	Minimum recorded load (kN/m^2)	Average recorded load (kN/m^2)	Maximum recorded load (kN/m^2)	Notes
1893	Boston Building Department [17]	210 offices in Boston - Rogers, Ames, Adams	7,103	0.78	1.35	1.90	-
1923	Blackall Clarence [18]	The Little Building, of Boston	-	0.06	0.38	0.70	Four offices had loading over 0.48 kN/m^2
1925	Report of Building Code Committee (NY, USA) [2]	193 offices at Equitable Office Building, New York, N. Y.	-	0.04	0.49	1.62	Light-occupancy floor (twentieth floor) - 67 offices
			-	0.16	0.51	1.47	Medium-occupancy floor (thirty-seventh floor) - offices
			-	0.30	0.67	1.62	Heavy-occupancy floor (eleventh floor) - 62 offices
1925	Report of Building Code	Office building in Cincinnati - M. W.	3,467	0.18	0.42	0.65	-

Year	Source	Building typology	Area (m^2)	Minimum recorded load (kN/m^2)	Average recorded load (kN/m^2)	Maximum recorded load (kN/m^2)	Notes
	Committee (NY, USA) [2]	McIntyre of the Union Central Life					
1967	Survey Results for Fire Loads and Live Loads in Office Buildings [19]	23 office buildings	6,579	0.28	0.58	0.90	335 rooms in total, 252 offices, corridors, lavatories, etc. were excluded
1970	CIRIA Report 25 [20]	office space	-	-	-	0.57	-
1971	Building Research Station [21]	32 Office buildings	162,800	0.62	1.13	1.66	include floors above ground floor, include mobile loadings, due to movement of heavy individual items or local concentrations of personnel, which it is not practicable to determine for every bay
1974	Survey Results for Fire Loads and Live Loads in Office Buildings [19]	23 office buildings	3,865	0.42	0.74	0.98	149 offices, corridors, lavatories, etc. were excluded
1982	A58.1 American National Standard [22]	office space	-	-	-	0.52	-
1986	Andam [23]	1353 rooms in	25,206	0.04	0.28	0.44	includes clerical, general space, reception, conference,

Year	Source	Building typology	Area (m^2)	Minimum recorded load (kN/m^2)	Average recorded load (kN/m^2)	Maximum recorded load (kN/m^2)	Notes
		Accra, Ghana					excludes: storage, file, library, corridor
1992	Fitzpatrick A. et al, Stanhope Properties [24]	Stanhope office, financial advisors office	for 19.9 and 33 m2	0.36	0.40	0.44	-
2018	Own calculations based on [25]	Larkin Administration Building, NY	395	-	-	0.57	designed for 4.88 kN/m^2
2018	Own calculations based on [26]	Taylorist Inspired Office	-	-	-	0.49	-

Real office loading is in the range 0.3 – 0.5 kN/m^2 on average.

2.3.1 Occupier density

In 2013 the British Council for Offices analysed analysed 2,485,484m^2 (26,753,753ft^2) of office space, spread across 381 properties and 1331 individual floors and found a mean density of one workplace per 10.9 m^2 net internal area [27] (Figure 5). Assuming one person weighs 0.74kN, this gives a loading from people of 0.07kN/m^2. BCO 2014 [3] and Homes and Communities Agency (2015) [28] suggest that density for work space should be within a range of 8-13m^2 per person, which gives a range for area loading of 0.09 - 0.06 kN/m^2. It should be feasible with this to estimate crowd loading, along with pattern loading on floors.

2.4 What does 100 psf look like?

To visualise historical “one hundred pounds per square foot” and 2.5 kN/m^2 of the UK NA to BS EN 1991, a floor load exercise was conducted as a part of MEICON project [29]. A full report of this exercised can be found online. In summary, normal use (ten people and furniture) yielded an area load of 0.54 kN/m^2. A maximum area load of 5.6kN/m^2 was achieved by squeezing 29 people into 3.75 m^2 of space (Figure 7).

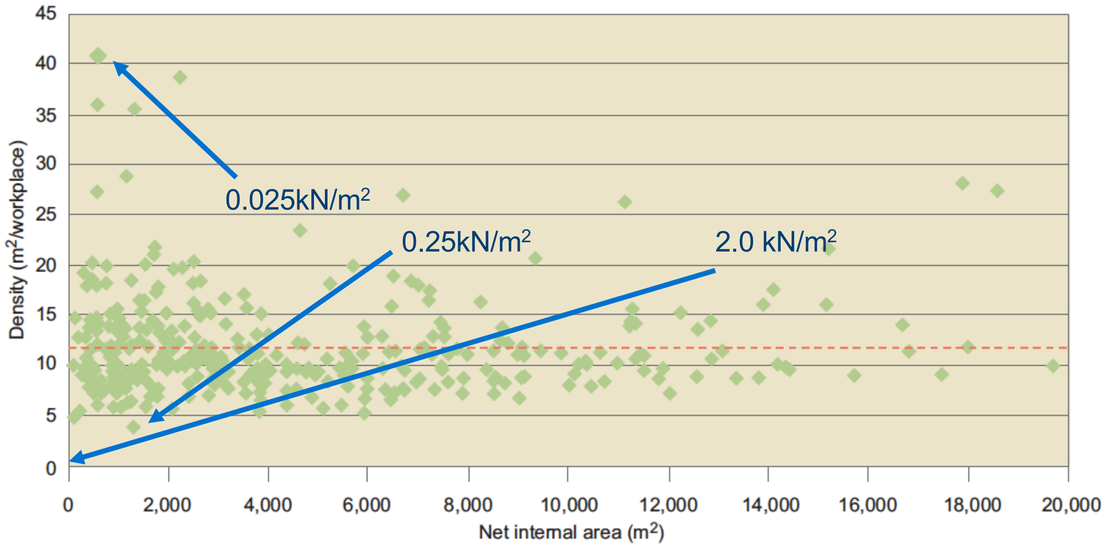


Figure 5 Occupier density study [27]

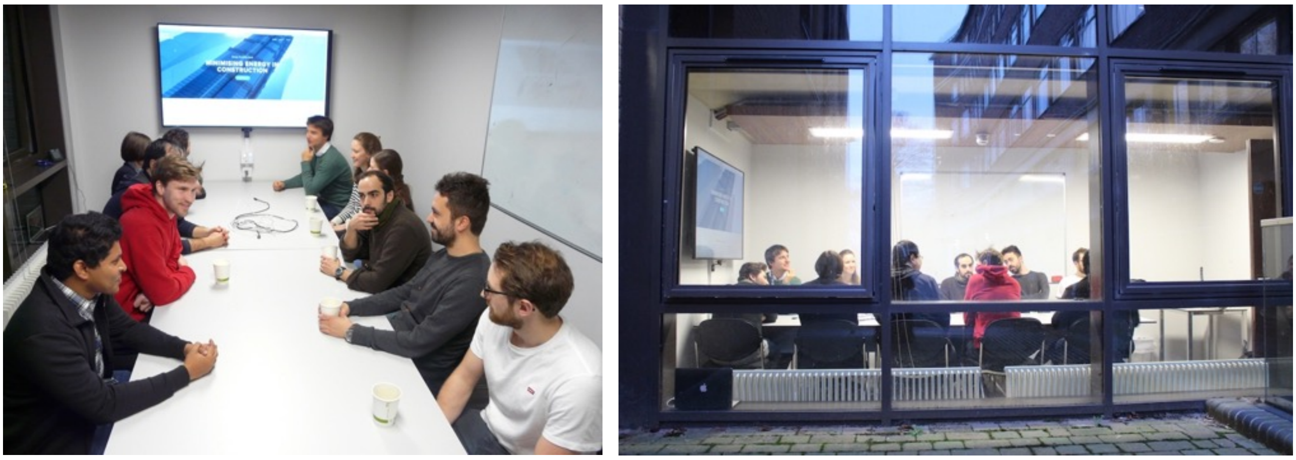


Figure 6: Meeting room in normal capacity, 0.54kN/m² [29]

Figure 7: 29 volunteers in 3.75 m² = 5.6kN/m² [29]

2.5 Summary of the live load assessment

The section has shown, in support of previous studies, that floor live load for offices in use is normally far below 1.0kN/m^2. Design for high than necessary loading may result in serviceability level calculations being undertaken on statistically extreme loading values, with the result being excess consumption of material.

The use of nominal loading values reflects the uncertainty we have in what real loading is, yet this could be solved by research into the use of sensing to measure real loading in buildings, to inform future design. Designers presently use high loading as a risk mitigation against this uncertainty.

3 Recommendations

1. Use floor loading values as recommended by the Eurocodes (for UK offices above ground floor, 2.5kN/m^2)
    a. Produce heat maps showing the as-built design load capacity of your structures and provide these to building operators.
    b. Compare heat maps of as-built capacity to the design requirement, and investigate any differences. Publish the reasons, and challenge your teams to reduce gaps.
2. Install measurement into products and projects to understand real loading over long periods of time
3. Build loading models based on measured data and compare to design assumptions.
4. Update floor live load values accordingly and measure the effect of such changes.
5. Repeat 2-4, using your structures as a living laboratory.

Figure 8: 5.6kN/m^2 (29 people in 3.75m^2)

Figure 9: More conventional use of meeting room (29 people in 72m^2, 0.30kN/m^2).

Chapter 2: Historical perspectives

4 History of Laws, Codes and Guidelines

Building Codes have a long history - dating back to 1772 BC with the code of Hammurabi [30]:

> *"If a builder builds a house for someone and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be put to death." [30].*

Between 30 and 15 BC, Roman architect and military engineer Marcus Vitruvius, wrote his treatise *De architectura* (On architecture, Ten Books on Architecture) a guide for building projects that gives personal knowledge of the quality of buildings [31]. Architecture and the role of architect was described as:

> *"Architecture is a science arising out of many other sciences, and adorned with much and varied learning; by the help of which a judgment is formed of those works which are the result of other arts. Practice and theory are its parents. (…) He (architect) should be a good writer, a skilful draftsman, versed in geometry and optics, expert at figures, acquainted with history, informed on the principles of natural and moral philosophy, somewhat of a musician, not ignorant of the sciences both of law and physic, nor of the motions, laws, and relations to each other, of the heavenly bodies."*

Vitruvius describes a building as follows:

> *"All these (buildings) should possess **strength, utility,** and **beauty**. Strength arises from carrying down the foundations to a good solid bottom, and from making a proper choice of materials without parsimony. Utility arises from a judicious distribution of the parts, so that their purposes be duly answered, and that each have its proper situation. Beauty is produced by the pleasing appearance and good taste of the whole, and by the dimensions of all the parts being duly pro portioned to each other."*

Vitruvius also presented the use of various materials due its strength and fire resistance:

> *"They (Romans) were then asked where they obtained this sort of wood, which would not burn. Thus, as the fortress was called Larignum, so the wood, whereof the tower was built, is called larigna (larch)."*

But what is most important Vitruvius introduced examples of some building behaviour:

> *"It is, moreover, a good practice to place posts under the lintels, between the piers and pilasters; for when lintels and beams are loaded, they sag in the middle, and cause fractures in the work above: but when posts are introduced and wedged up under them, the beams are prevented from **sagging and being injured**."*

First regulations in England were dated to around 1189 [32]. They were focused on fire prevention due to the use of flammable materials and densely packed housing. After a major fire in London in 1212 the city's first mayor, Henry fitz Ailwin, banned thatched roofs [33]. Due to the danger of fire Worcester's ordinances of 1467 prohibited using of thatch and timber chimney in building located within the town walls [34].

After the Great Fire of London in 1666 the first Re-Building Act 1666 [35] specified materials that should be used in different types of building, along with proportions and standard dimensions for houses within the City of London. This Act required that all houses were to be built in brick and stone. Further Acts of 1707 [36] and 1709 [37] extended the control to Westminster. The Act of 1774 [38] covered the whole built up London's area. These acts became a prototype for almost 400 Acts accepted between 1800 and 1845 in 208 towns in England and Wales [39, 40]. Due to the fact that cities' Acts described general rules, in the 18th century a development of carpenters' manuals began.

Carpenter's manuals started to be more advanced in case of illustrations and details of construction [41]. Neve in *The City and Country Purchaser, and Builder's Dictionary* (1703) pointed out that in the literature there is a lack of any general rules for determining the sizes of buttresses to resist the thrust of arches [42].

The City and Country Purchaser, and Builder's Dictionary guide the choice of size members according to the Re-Building Act 1666 [35] Figure 10. For longer span it was advised to use "a pair of *Prosts* in the middle" to avoid Figure 11, Figure 12). This Dictionary also presented rules for Joints (Figure 13).

2. *The Size.*] The *Beams*, according to an Act of Parliament, for the Re-building of the City of *London*, after the dreadful Fire, were appointed to be of the following Scantlings, *viz.*

	Foot		Inch		Inches.
In length	15	must be in that Square.	7	and	5
	16		8		6
	17		10		6

Figure 10: Size of beams: The City and Country Purchaser, and Builder's Dictionary (1703) pp. 30-31 [42]

Bay.

This word is used, to signifie (as it were) the Magnitude of a *Barn*; for if a Barn consist of a Floor, and 2 Heads, where they lay Corn, they say a Barn of 2 *Bays*; these *Bays* are from 14, to 20 Foot long, and Floors from 10 (which is the smallest size) to 12 broad, and usually 20 long, which is the breadth of the Barn: If a *Bay* be 20 Foot long, then there is commonly a pair of *Prick-posts* in the middle, and a *Beam* to hold in the Rod from bending the Raisons; but if the *Bays* are not above 16 Foot, and the Timber stout, then there is no *Posts*, but at the end of each Bay, where there is always hanging *Braces*, Framed into the *Beam*, and *Posts*, and also a cross *Cell* to hold in the side *Cells* from flying out when the *Barn* is fill'd, and 'tis common for large Barns to consist of divers such *Bays*.

Figure 11: Definition of the Bay: The City and Country Purchaser, and Builder's Dictionary (1703) pp. 29-30 [42]

Bearing?

The Anſwer to ſuch a Demand, or Queſtion, ſuch a piece of Timber has, is 10, 12, 15, &c. Foot, according to the length of the whole Timber, or elſe according to the diſtance between either end of the Timber; and a

Bearer.

Viz. A Poſt, or Brick-wall, that is Trimed up between the ends of a piece of Timber to ſhorten its *bearing*.

Figure 12: Bearing: The City and Country Purchaser, and Builder's Dictionary (1703) pp. 31 [42]

Joyſts.

1. *What.*] Joyſts, in Architecture, are thoſe pieces of Timber (fram'd into the Girders and Summers,) on which the Boards of the Floors are laid.

2. *Scantlings.*] Joyſts at full length (to bear in the Wall,) I ſay, their full length

being { 12 Foot, / 11 Foot, 6 Inches, / 10 Foot, 6 Inches, } they ought to be in their

Squares { 8 Inches and 3 Inches. / 7 Inches and 3 Inches. / 6 Inches and 3 Inches. }

And Binding, or Trimming-joyſts being

in length { 7 Foot, / 9 Foot, / 11, or 12 Foot, } ought to be in their

Squares { 6 Inches, and 5 Inches. / 7 Inches, and 5 Inches. / 8 Inches, and 5 Inches. }

Figure 13: Joists: The City and Country Purchaser, and Builder's Dictionary (1703) pp. 184-185 [42]

Fifthly, That no *Joyſts*, or *Rafters* be laid at greater diſtances from one to the other; than 12 Inches; and no *Quarters* at greater diſtance than 14 Inches.

Sixthly, That no *Joyſts* bear at longer length than 10 Foot; and no ſingle *Rafters* at more in length than 9 Foot.

Figure 14: Some general rules: The City and Country Purchaser, and Builder's Dictionary (1703) pp. 72 [42]

4.1 Analysis

Adopting some of the prescribed member dimensions it is possible to back-calculate approximate deflection and load capacities for historic member sizes. In order to do this we can make some assumptions on the material properties, taking typical bending strengths for timber.

Moment capacity is calculated using Eq. (1):

$$M = \frac{I(\sigma_{max})}{y} \quad (1)$$

Where σ_{max} - bending strength parallel to grain, taken here from BS 5268-2 as 12.5 N/mm^2 for oak (strength class THA/D40 [43, 44]), *I* is the second moment of area of the section, *y* is the distance from neutral axis to extreme fibre.

From which an allowable load can be calculated, using Eq. (2):

$$w = \frac{8M}{L^2} \quad (3)$$

Allowable deflections, assuming line loading on the beam, can be calculated from Eq. (3):

$$\delta = \frac{5wL^4}{384\,EI} \quad (3)$$

Where E – Elastic Modulus for English Oak and European Oak taken as a mean value from [44], 12.3 GPa for strength class D40.

Table 2: Historical floor load capacity

Length m (feet)	H mm (inch)	B mm (inch)	Allowable bending stress - oak MPa	Moment capacity M (kNm)	Load w (kN/m)	Load for 3.65 m (12 feet) broad floor (according to Figure 11) kN/m^2	Deflection in mm for load "w" 5wL^4/384 EI	Deflection
As prescribed in Figure 10								
4.6 (15)	178 (7)	127 (5)	12.5	8.4	3.2	0.9	25.2	L/183
4.9 (16)	203 (8)	152 (6)	12.5	13.0	4.3	1.2	25.0	L/196
5.2 (17)	254 (10)	152 (6)	12.5	20.4	6.0	1.7	22.5	L/231
Shortest span using the largest cross-section								
4.6 (15)	254 (10)	152 (6)	12.5	20.4	7.7	2.1	17.6	L/261
20 foot bay x 12 foot wide, divided by half (two 10 x 12 foot) - Figure 11								
3.05 (10)	254 (10)	152 (6)	12.5	20.4	17.6	4.8	7.8	L/393

Table 2 appears to demonstrate that the rules of thumb for historic design result in floor loadings (kN/m^2) that are usually less than is used in design today.

4.2 Case Study

To find the load capacity of historical buildings, one of floor structure from 16th century building located in Cambridge was analysed. The Brewhouse at Peterhouse College, University of Cambridge (Figure 16) was built for domestic purposes and consists of four bays. The floor load capacity of the oldest part, Bay 4, was investigated. Calculations were made using the same approach as above.

Analysing The Brewhouse floor (Bay 4 – 13x14 foot, presented on Figure 16), we can find that the main beam (10x7 inch) located in the middle of the Bay 4 (13 foot long, width 14 foot) can bear the floor load of 5kN/m^2 (Table 3) with slightly higher deflection than L/360 limits.

Table 3 The Brewhouse – Peterhouse College, Cambridge

Span (m)	H mm (inch)	B mm (inch)	Bending stress - oak (MPa)	Moment capacity, (kNm)	Maximum load, w kN/m	Load taken from the half of the width kN/m^2	Deflection in for load "w" (mm) 5wL^4/384EI	Deflection
3.96	254 (10)	178 (7)	12.5	23.9	12.2	5.7	13.1	L/303

Figure 15: The Brewhouse – entrance for the room (left), Bay 4 floor structure (right)

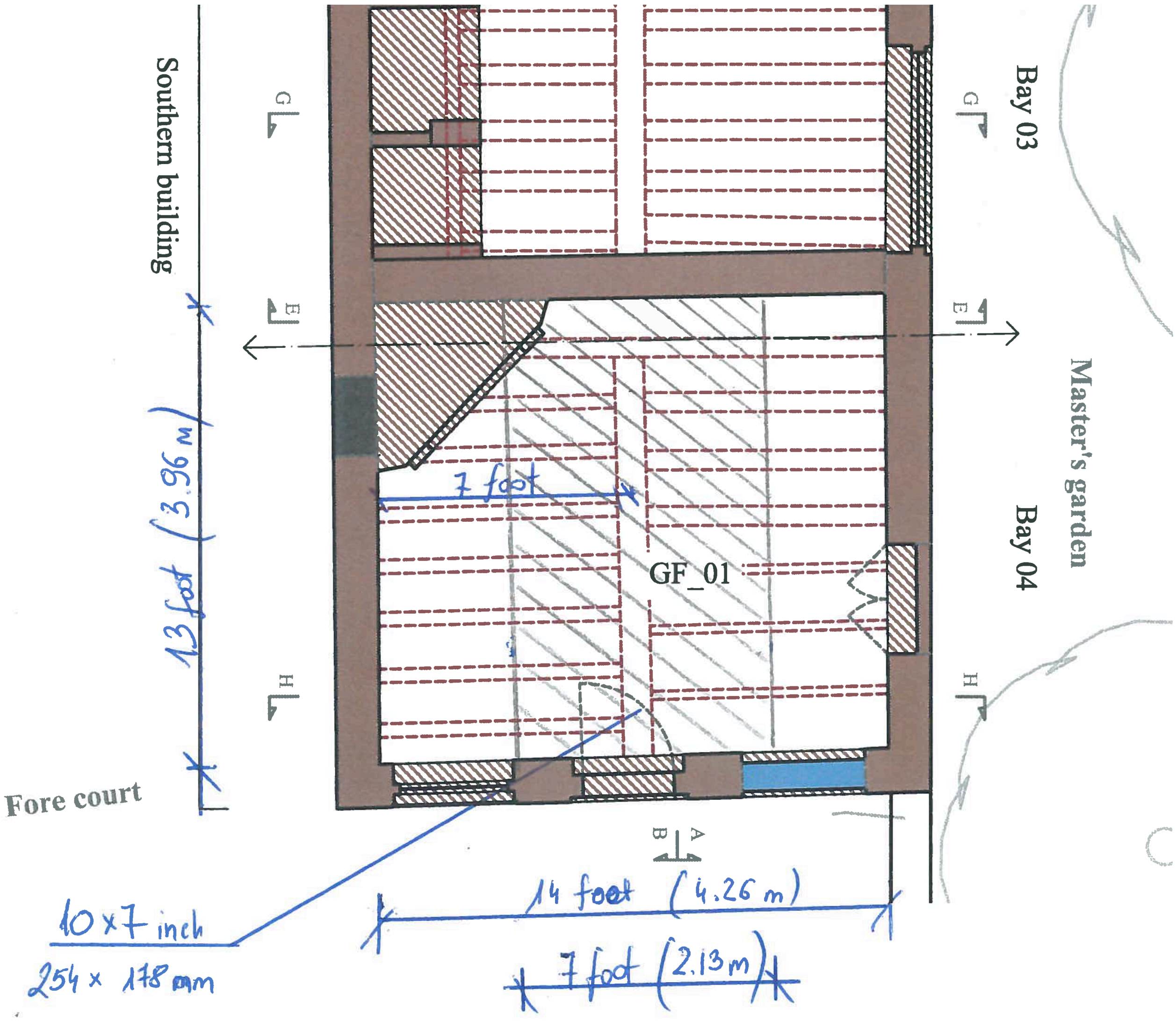


Figure 16: The Brewhouse, Bay 4 [45]

4.3 Structural guidelines from the 18th and 19th and deflection limits

In 18th century, the first author who successfully handled both geometry and construction was a clerk of works at Salisbury Cathedral Francis Price [41]. Price's *A Treatise on Carpentry* (1733) [46] became a manual for the carpenters in their daily work who had to deal different structures. The book was extended and finally six editions were published, the last in 1769. This book presented the way how beams and joints should be placed than guide what beams should be used.

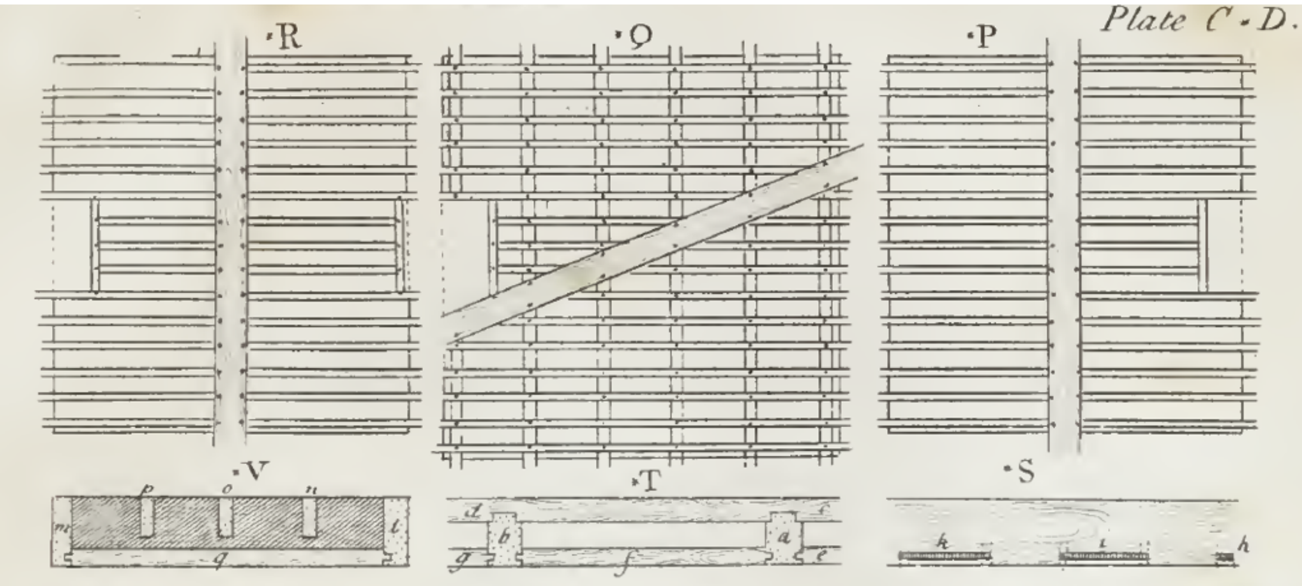


Figure 17: Floor plate [46]

With an increasing demand for building new structures types and structural solutions were introduced, that uses less material – use of trusses and new types of floor structures [47]. The common practice was to use trussing to stiffen long span girders [48]. James Smith at *The Carpenter's Companion* (1733) produced a collection of drawings with specific comments addressed to carpenters [49].

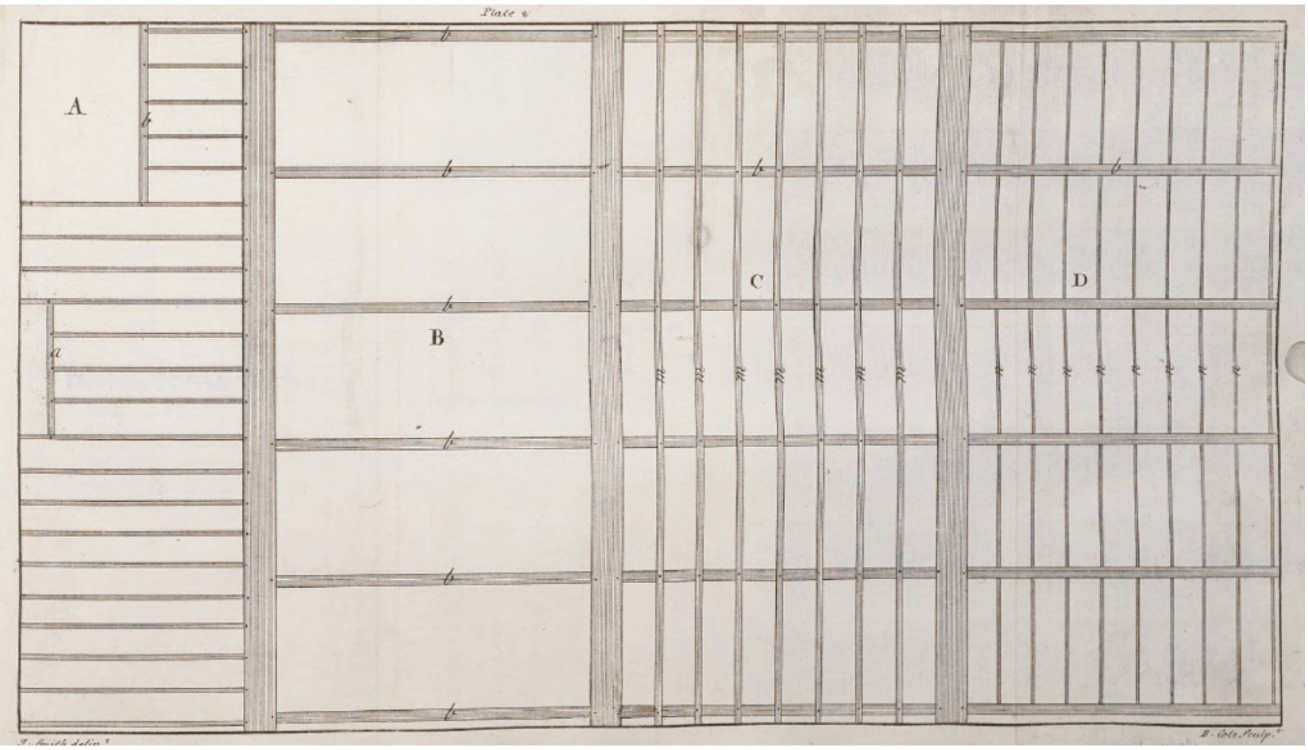
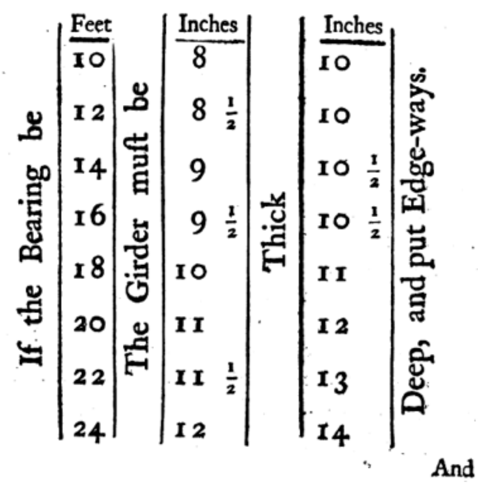


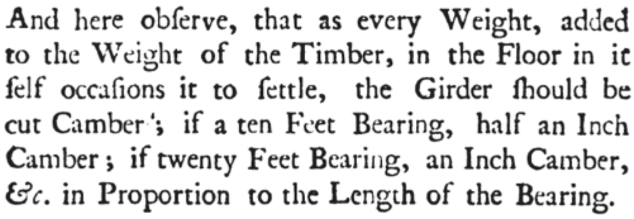
Figure 18: Floor plate [49].



If the Bearing be	Feet	The Girder muft be	Inches	Thick	Inches	Deep, and put Edge-ways.
	10		8		10	
	12		8 ½		10	
	14		9		10 ½	
	16		9 ½		10 ½	
	18		10		11	
	20		11		12	
	22		11 ½		13	
	24		12		14	

And

Figure 19: Girder proportions [49].



And here obferve, that as every Weight, added to the Weight of the Timber, in the Floor in it felf occafions it to fettle, the Girder fhould be cut Camber; if a ten Feet Bearing, half an Inch Camber; if twenty Feet Bearing, an Inch Camber, &c. in Proportion to the Length of the Bearing.

Figure 20: Girder proportions [49].

To find the floor load capacity of the girders presented in Figure 20, calculations were made assuming that the floor bays are square (i.e. 10x10 foot or 14x14 foot), similar to Figure 18. For the length more than 20 foot, the bay is divided in the middle after Figure 11. It was found that for square bays 10x10 and 12x12 foot, floor load capacity was higher than more than 4.7 kN/m^2, decreasing to 2 kN/m^2 in square 18x18 foot bay. For rectangular bays, the floor capacity was found to be more than 3.3 kN/m^2.

Table 4 Historical floor load capacity

Bay size m (foot) length x width	H mm (inch)	B mm (inch)	Bending stress - oak (MPa)	Moment capacity, kNm	w kN/m	Floor load (square bays, over 20 foot, bay divided in the middle) kN/m^2	Deflection in for load "w" (mm) $5wL^4/384EI$	Deflection
Square bays								
3.05x3.05 (10x10)	254 (10)	203 (8)	12.5	27.3	23.5	7.7	7.7	L/394
3.7x3.7 (12x12)	254 (10)	216 (8.5)	12.5	29.0	17.4	4.7	11.2	L/328
4.3x4.3 (14x14)	267 (10.5)	229 (9)	12.5	33.9	14.9	3.5	14.5	L/295

4.9x4.9 (16x16)	267 (10.5)	241 (9.5)	12.5	35.8	12.0	2.5	18.9	L/258
5.5x5.5 (18x18)	279 (11)	254 (10)	12.5	41.3	11.0	2.0	22.8	L/241
Rectangle bays								
6.1x3.05 (20x10)	305 (12)	279 (11)	12.5	54.1	11.6	3.8	25.8	L/236
6.7x3.35 (22x11)	330 (13)	292 (11.5)	12.5	66.4	11.8	3.5	28.8	L/233
7.3x3.7 (24x12)	355 (14)	305 (12)	12.5	80.3	12.0	3.3	31.9	L/230

Hawksmoor et al. in *The Builders' Dictionary* (1734) [50] discussed the strength of timber beams and presented the resistance to bending is proportional to the width and the square of the depth. The dictionary also recognized different loads: “own Weight” and “other foreign Weights” (Figure 21). Nevertheless, they pointed out that the sizes should be taken as from the Re-Building Act 1666 [35].

A *Beam* may be ſuppoſed to be either loaden only with its own Weight, or with other foreign Weights, apply'd at any Diſtance, or only with thoſe foreign Weights. Since, according to M. *Parent*, the Weight of a *Beam* is not ordinarily above one ſeventieth Part of the Load given to ſuſtain it, it is evident, that in conſidering ſeveral Weights they muſt be all reduced by the common Rules, to one common Centre of Gravity.

M. *Parent* has alſo calculated Tables of the Weights, which will be ſuſtain'd by the Middle in *Beams* of various Baſes and Lengths, fitted at each End, into Walls, on a Suppoſition, that a Piece of Oak of an Inch ſquare, and a Foot long, retain'd Horizontally by the two Extreams, will ſuſtain three hundred and fifteen Pounds in its Middle before it breaks; which, it has been found by Experiments, that it will. See *The Memoirs of the* French *Academy*, Anno 1708.

Figure 21: Beam loads: The Builder's Dictionary: Or, Gentleman and Architect's Companion (1734) [50]

As to the Size of Beams. The Proportions of Beams in or near *London*, are fix'd by a Statute or Act of Parliament for the rebuilding of the City of *London*, after the Fire in 1666, and were appointed to be of the following Scantlings.

Figure 22: Sizes of the beams: The Builder's Dictionary: Or, Gentleman and Architect's Companion (1734) [50]

In the 19th century Barlow's *An Essay on the Strength and Stress of Timber* (1817) [51] and its incorporation into Tredgold's *Elementary Principles of Carpentry* (1820) [52] presented a wide research of timber, iron, cables, chains and other metals strength. Barlow provided a table of data and ways of finding a strength of different materials based on this data.

Due to The Industrial Revolution (1760-1830 [53]), and the associated diversity of building types and growth of London, The Metropolitan Building Act of 1844 [54] was introduced. The Act regulated the construction and use of buildings in the metropolitan area of London and classified buildings into three types - dwelling houses, warehouses and public buildings. The Local Government Act of 1858 [55] extended the powers of England and Wales local authorities to regulate the structure of buildings through Bye-laws [18].

One of the first books that introduced structural calculation was *An Encyclopædia of Architecture: Historical, Theoretical, and Practical* by Joseph Gwilt, published in 1841 [56]. The book presented structural material characteristics, for stone, timber, and steel. Gwilt described "a relative" and "absolute" strength, where absolute describes strength "by pulling in in the direction of the fibres" whereas relative as bending strength of simple supporting beam. Bending strength "depends upon its position".

> *" (…) a piece 8 ft. long and 6 in. square placed horizontally, bears a little more than double of another, of the same depth and thickness, 16 ft. long, placed in the same way." [56], pp. 441*

Gwilt also provided an experiment results conducted by Buffon upon beams 4.264, 5.330, 6.396, 7.462, 8.528 inches square, of different lengths, as well the greatest strength of oak timber lying horizontally. Tests were conducted on simply supported beams with point loads.

Table VI.

Showing the greatest Strength of Oak Timber lying horizontally, in pounds averdupois.

Length of each Piece in English Feet.	Proportion of Depth to Length.	Breaking Weight in lbs. averdupois.	Length of each Piece in English Feet.	Proportion of Depth to Length.	Breaking Weight in lbs. averdupois.	Length of each Piece in English Feet.	Proportion of Depth to Length.	Breaking Weight in lbs. averdupois.
3·198 inches (Eng.) square.			**3·198 in. by 5·330 in.**			**4·264 inches square.**		
1·599	6	12245	2·664	6	20418	2·842	8	16224
2·132	8	8747	3·553	8	15109	3·553	10	12728
2·664	10	7163	4·441	10	11934	4·264	12	10469
3·198	12	5889	5·330	12	9815	4·974	14	8696
3·730	14	4980	6·218	14	8303	5·685	16	7645
4·264	16	4290	7·106	16	7167	6·396	18	6702
4·796	18	3771	7·994	18	6283	7·106	20	5951
5·330	20	3247	8·883	20	5578	7·817	22	5333
5·862	22	3000	9·771	22	5010	8·528	24	4820
6·396	24	2711	10·660	24	4519	9·238	26	4386
6·928	26	2447	11·548	26	4111	9·949	28	4014
7·469	28	2257	12·436	28	3758	10·66	30	3686
7·994	30	2076	13·324	30	3459			

Figure 23: The greatest strength of oak timber lying horizontally (a part) [56],

Gwilt also provided a method to find the strength of a beam (Figure 24):

Method of using the above Table for horizontal Timbers.

1625. To find the strength of a beam of fir 23·98 ft. long and 5·330 by 9·594 in. Against these dimensions in the Table VI. we find 10378 as the breaking weight. In the Table VII. we find the primitive horizontal strength of oak is to that of fir as 1000 to 918. Hence 1000 : 918 :: 10378 to a fourth term which = 9527; which expresses the greatest strength of such a beam of fir, or that which would break it. Cutting off the last figure on the right hand, that is, taking one tenth, we have 952 for the greatest weight with which such a beam should be loaded.

1626. If the beam be of chesnut, whose primitive strength is 957, the proportion becomes 1000 : 957 :: 10378 : 9931 = the greatest strength of such a piece, and $\frac{9931}{10}$ the greatest weight with which it should be loaded.

Figure 24: Mechanical Carpentry – Method to find the strength of a beam: "An Encyclopædia of Architecture: Historical, Theoretical, and Practical" published in 1841 pp. 456 [56]

From [56] we can find that for a simply supported beam subject to a point load W, the maximum design load is 4.23kN (952lbf), giving deflections of L/377 (Table 5). This was derived in [56] by taking design loads simply as 10% of the expected breaking load, and yields a deflection limit similar to L/360 used today.

Table 5 Strength of a timber beam according to [56] and maximum load that meet deflection criteria L/360

Beam length L m (foot)	H mm (inch)	B mm (inch)	Design load, W, according to [56] kN (lbf)	Design moment capacity according to [56] kNm (WL/4)	Deflection in mm for load "W" [56] $WL^3/48EI$	Deflection compared to span	Point load when use deflection criteria **L/360** kN	Load ratio (experiment [56] / load to meet deflection criteria
7.31 (23.98) (Fir, E = 11GPa	243 (9.594)	135 (5.33)	4.23 (952 – Figure 24)	7.73	19.4	L/377	5.0	1.54

Gwilt also described different materials used in buildings, introduced steel as material that started to be used more often (Figure 25) providing the way of finding ultimate strength for iron beam (Figure 26).

1767. The security afforded, not only for supporting weight, but against fire, has, of late years, very much increased the use of it, and may in many cases entirely supersede the use of timber. Again, it is valuable from its being not liable to sudden decay, nor soon destroyed by wear and tear, and, above all, from its plasticity.

Figure 25: Mechanical Carpentry – Iron pp. 494 [56]

1772. Problem I. To find the ultimate strength of a rectangular beam of cast iron supported at both ends, and loaded in the middle, we have only to multiply the breadth into the square of the depth, and that again by the constant 2580, and the last product divided by the length in feet will be a quotient expressing the weight in pounds averdupois, nearly.

Example. What weight will break a cast iron beam 2 inches broad, 6 inches deep, and 15 feet between the supports?

$$\text{Here } \frac{2580\times 2\times 6^2}{15}=12384 \text{ lbs.}$$

If a beam be supported at the middle and loaded at each end, it will bear the same weight as when supported at both ends and loaded in the middle. It may be here observed, that the following rules hold good for inclined as well as horizontal beams, if the horizontal distance between the supports be taken for the bearing.

Figure 26: Mechanical Carpentry – Ultimate strength pp. 494 [56]

In Figure 26 the breaking load of a 2" x 6" deep, 15' span beam is given as 12,384lbs, which is 55.1kN. As a point load placed in the midspan, this suggests a moment capacity of 62.9kNm. By comparison, assuming E = 210GPa, and a yield stress of 350MPa, we obtain a breaking load (simply supported, mid span) of 60kN using the Engineer's equation (9% increase). Whilst the example in Figure 26 is given for a rectangular cross section, Gwilt [56] does highlight the "strongest form" as being an I-beam (Figure 27). To calculate design loading, Gwilt [56] proposes to take 1/3 of the calculated breaking load.

its elasticity, we thus obtain constants for guiding us in the ordinary computations for the sizes of girders, beams, bressummers, &c. The strongest form of the section of a beam to resist a cross strain is this I. We do not however think it here necessary to give much more than the rules for finding their breadths and depths, considered as simple figures. The principles on which the rules subjoined are founded may be seen in Gregory's *Me-*

Figure 27: "strongest form" for Iron beam, from [56]

None of the analysed guidelines published between 18th and 19th century (Table 6) present deflection limits. It might be concluded that strength of elements was the main driver for design choices.

In 1850 Nicholson, Gunyon, and Lomax in *Encyclopedia of Architecture: A Dictionary of the Science and Practice of Architecture, Building, Carpentry* [57] to Vitruvius' building definition by use materials in more economy way and that:

> *"(…) the greatest amount of strength be secured the smallest expenditure of material" [57], pp.25.*

5 Development of Laws, Codes and Guidelines

With the urban development in the US in the mid-nineteenth century, since 1859 the building regulations were accepted in New York, Boston, Chicago and Baltimore [58].

In 1860 The Laws of New York State [1] started to regulate the construction and use of buildings [59].

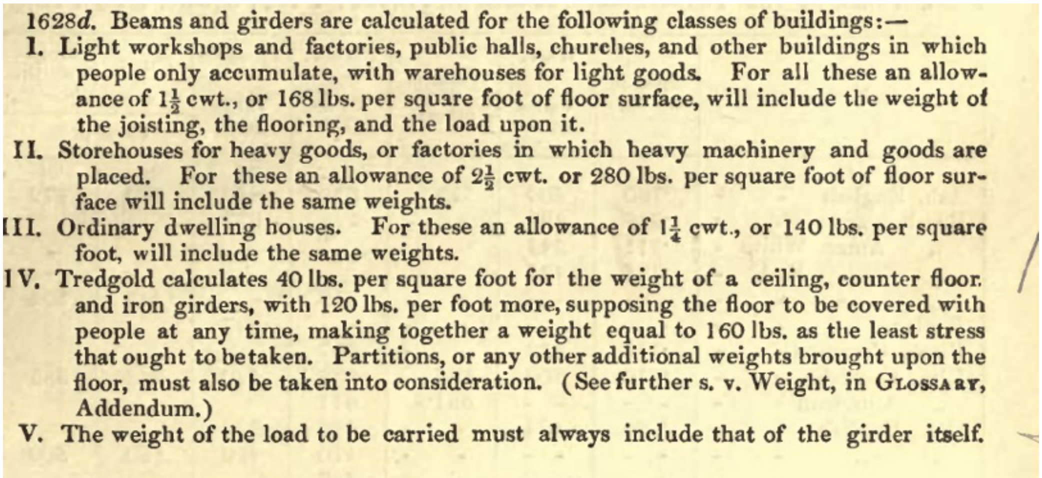
The Laws of New York State 1860 (Chapter 470) [1] state:

> *"In every building, the floor shall be on sufficient strength to bear the weight to be imposed upon them, exclusive in all cases of the weight of material used in their construction; and if at any time the said building shall be loaded over the said weight, it shall be at the risk of occupant, whatever the same be the owner or not."*

However, the 1860 Act [1] did not introduce values required for the imposed loads, which were only added in 1862:

> *"In all buildings, every floor shall be sufficient strength, in all its parts, to bear safety upon every superficial foot of its surface**, seventy-five pounds**; and if used as a place of public assembly, **one hundred and twenty pounds**; and if used as a store, factory, warehouse, or for any other manufacturing or commercial purposes, **from one hundred and fifty** to five hundred pounds upwards;"* pp.586 [60]

Almost twenty years later, in 1881, the second edition of *An Encyclopædia of Architecture: Historical, Theoretical, and Practical* [12] introduced guidelines for floor loading. For dwellings it was suggested 140psf including self-weight (estimated by [61] as 40 psf, making the live load 100 psf (4.80 kN/m^2)), for light workshops and factories, public halls, churches and other buildings in which people only accumulate 168 psf including self-weight (giving a live load of ~128 psf (6.13 kN/m^2)) (Figure 28) [12].



1628*d.* Beams and girders are calculated for the following classes of buildings:—

I. Light workshops and factories, public halls, churches, and other buildings in which people only accumulate, with warehouses for light goods. For all these an allowance of 1½ cwt., or 168 lbs. per square foot of floor surface, will include the weight of the joisting, the flooring, and the load upon it.

II. Storehouses for heavy goods, or factories in which heavy machinery and goods are placed. For these an allowance of 2½ cwt. or 280 lbs. per square foot of floor surface will include the same weights.

III. Ordinary dwelling houses. For these an allowance of 1¼ cwt., or 140 lbs. per square foot, will include the same weights.

IV. Tredgold calculates 40 lbs. per square foot for the weight of a ceiling, counter floor, and iron girders, with 120 lbs. per foot more, supposing the floor to be covered with people at any time, making together a weight equal to 160 lbs. as the least stress that ought to be taken. Partitions, or any other additional weights brought upon the floor, must also be taken into consideration. (See further s. v. Weight, in Glossary, Addendum.)

V. The weight of the load to be carried must always include that of the girder itself.

Figure 28: Chapter I, Beams and Pillars, "An Encyclopædia of Architecture: Historical, Theoretical, and Practical" in 1881, pp. 429 [12].

In 1886 Kidder, in *The architect's and builder's pocket-book* [13] introduced the factor of safety for live load calculations:

> *"It has been found by experience that the effect of live load on a beam or other piece of material is twice as serve as that of dead load of the same weight: hence a piece of material designed to carry a live load should have a factor of safety twice as large as one designed to carry a dead load" pp.127*

The manual guide what floor live load might occur in a panic or some unusual circumstances:

> *"(…) in a panic or some unusual circumstance, is it possible to get a weight on the floor of one **hundred and twenty pounds per square foot**." pp. 354*

Kidder suggested the imposed load of 40 psf and 100 psf for dwellings and storage of grain respectively should be assumed.

In 1891 The Laws of New York State introduced slightly different buildings classification than earlier The Laws of New York State (e.g. from 1871 [62]):

> *"Floors (…) shall be constructed to bear a safe weight, per superficial foot, exclusive for materials (…) For dwelling-houses, tenement-houses, apartment-houses, hotels, boarding-houses* ***and*** *stables, not less than* ***seventy pounds****; ordinary school-rooms and rooms for light mechanical purposes, not less than one* ***hundred pounds****; theaters, public halls, churches and all rooms liable to be crowded with people, not less than one hundred and twenty-five pounds; stores, factories, mills and business buildings, not less than one hundred and fifty pounds; storehouses, warehouses, machine shops, armories and drill-rooms, not less than two hundred and fifty pounds." pp. 563*

The first act that distinguished office buildings was The Laws of New York State 1894 [5]:

> *"In every building used as a dwelling-house, tenement-house, apartment-house or hotel each floor shall be of sufficient strength in all its parts to bear safely upon every superficial foot of its surface* ***seventy pounds****. If to be used for office purposes, not less than* ***one hundred pounds*** *upon every superficial foot." pp. 1022*

Dorman, in the *Hand-book of steel sections* (1895) [63] suggests office floor loading should be taken as 80 psf. A slightly lower value of 70 psf was introduced in 1899 in *A treatise on architecture and building construction* by the International Correspondence Schools [64].

A value ranging between 70-80 psf was introduced in 1903 in *Appleby's Illustrated Handbook of Machinery* [65] whereas next editions of Kidder's Pocket Book i.e. from 1905 [66] suggested live load for office buildings should be taken as 80psf for ground floor office building and 60 psf for floors above.

The first Building Code approved by Mayor of New York City in 1899 and published in *The Building Code of the City of New York* in 1901 [67] defined an office building as:

> *"An office building shall be taken to mean and include every building which shall be divided into rooms above the first story, and be intended and used for business purposes, and no part of which shall be used for living purposes, excepting only for the janitor and his family." pp.13.*

And introduced

> *"Every floor shall be of sufficient strength to bear safely the weight to be imposed there on in addition to the weight of the materials of which the floor is composed (…) if to be used for office purposes not less than* ***seventy-five pounds*** *upon every superficial foot above the first floor, and for the latter floor one hundred and fifty pounds;" pp.111*

Shortly after this in the UK *The London Building Acts 1909* [68] introduced:

> *"The superimposed load in respect of a building shall consist of all loads other than the dead load: (…) For a floor intended to be used wholly or principally for the*

purpose of an office or a counting house or for any similar purpose **one hundred pounds per square foot of floor area**" *(4.80 kN/m²)*

Since the beginning of 20th century evolution of minimum values for live loads in office buildings led to accept a range of minimum values for offices in the range of 2 – 3 kN/m² in BS EN 1991-1-1 in 2002 [8]. The UK National Annex to BS EN 1991-1-1 [69] introduces 2.5 kN/m² for floors above ground floor and 3.0 kN/m² at or below ground level [70]. In the US the current standard ASCE 7 [71, 72] present live load value for office buildings of 2.4 kN/m² (50psf) [72]. All acts, building laws, codes, and guidelines included in this report are included in Table 6.

6 Summary

"Unrealistic design loads should not be used when it is impossible to generate that load or when, with a little forethought and simple guidelines on activity, high loading can be avoided." Hume, Miller [4]

Live load values are usually obtained from experience, are infrequently based on statistical analysis of measured data, and therefore understanding the behaviour of a floor in-service may be key to preventing widely over specification of floor spaces.

In the last one hundred years floor live loads requirements in codes for office buildings have dropped by a half from 4.8kN/m² (100psf) [5, 68] to 2.4kN/m² in the US [72] and 2.5kN/m² in the UK [69] Figure 29. Similar values were found for 64 countries [10]. Despite floor live load values in codes for office buildings being at the level of 2-3 kN/m², it has been noted that buildings are often designed for the higher load capacity:

"In the last decade commercial office buildings have been commonly designed for general super-imposed loading in the range of 3.5kN/m² (70lb/ft²) to 5kN (100lb/ft²)(…)" (1996) [24]

That is very close to "*one hundred pounds per square foot*" introduced more than hundred years ago and is five times higher than live loads found from the buildings live load assessment (1.0 kN/m²).

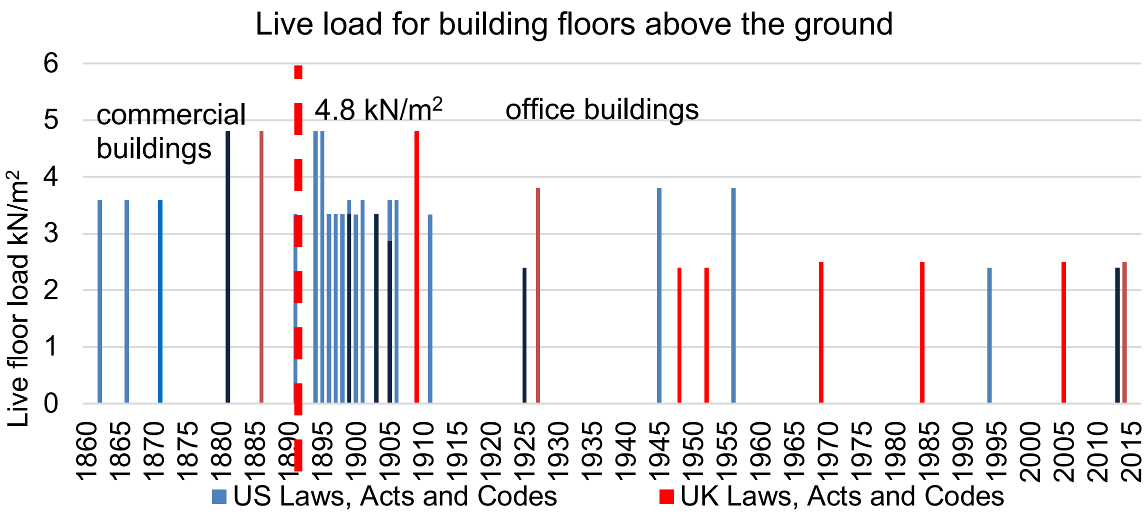


Figure 29: Floor live load for buildings (prior 1894 – commercial, after 1984 – office buildings)

6.1 Implications

Live load overspecification may lead to an increase in construction costs and increase environmental impact. Acheng [73] concluded that a 0.5kN/m^2 reduction in the design loads could result into a 20% reduction in the building costs and a 14% reduction in the overall embodied carbon of the structure [73]. Addressing real loading in buildings, through sensing and learning from performance, are key research challenges that must now be addressed if we are to minimise whole life carbon.

6.2 Research and Industrial Questions

This report links to key questions made in the MEICON project, taken from our report published in 2018 (www.meicon.net/survey2018):

IQ4: What might the benefit be of design code floor loading values being based on data gathered from a systematic global survey of loading levels in buildings?

IQ5: What might the unintended consequences be of changing live load values at ULS based on measured data?

IQ6: What might the unintended consequences be of changing live load values at SLS based on measured data?

IQ7: How might real time building loading information be integrated into building management systems to provide "traffic light" load levels to aid facility management?

RQ2: How can continuous measurement of floor loading in real buildings be used to provide certainty to the statistical basis for SLS loading, and how can this data be used to understand the extent to which loading conditions are "peaky" so that decisions about SLS requirements can be made?

RQ3: What is the real envelope of floor loading for which most designs should be undertaken?

RQ4: What might the benefits and consequences be of reducing material and load partial safety factors?

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Chapter 4: Appendices

7 Building Law / Regulations / Codes and guidelines within US and UK

Table 6 Building Law / Regulations / Codes and guidelines within US and UK

Year	Laws, Codes and Guidelines	Office building			
		Ground floor		Upper floor	
		psf	kN/m²	psf	kN/m²
	Learning from experience – First Laws, Codes and Guidelines				
1592	Tectonicon Digges L. [74]	-	-	-	-
1663	Council and Advice to All Builders [75]	-	-	-	-
1663	The First Book of Architecture [76]	-	-	-	-
1667	Mechanic exercise [77]	-	-	-	-
1670	Mechanica [78]	-	-	-	-
1703	The City and Country Purchaser, and Builder's Dictionary [42]	-	-	-	-
1733	A Treatise on Carpentry [46]	-	-	-	-
1733	The Carpenter's Companion [49]	-	-	-	-
1734	Builders' Dictionary [50]	-	-	-	-
1738	Gentleman's and Builder's Repository[79]	-	-	-	-
1740	The City and Country Builder's and Workman's Treasury of Designs [80]	-	-	-	-
1741	The Builders Jewel [81]	-	-	-	-
1744	Practical Builder [82]	-	-	-	-
1778	Carpenter and Joiners' Repository [83]	-	-	-	-
1781	Golden Rule [84]	-	-	-	-
1794	Practical house carpenter [85]	-	-	-	-
1786	British Palladio[86]	-	-	-	-
1797	The Carpenter and Joiner's Assistant [87]	-	-	-	-
1817	An Essay on the Strength and Stress of Timber (1817) [51]	-	-	-	-
1820	Elementary Principles of Carpentry [52]	-	-	-	-
1842	An Encyclopædia of Architecture: Historical, Theoretical, and Practical (London, UK) [56]	120	5.7	-	-
1844	The Metropolitan Building Act of 1844 (London, UK) [88]	-	-	-	-
1850	Encyclopedia of Architecture: A Dictionary of the Science and Practice of Architecture, Building, Carpentry [57].	-	-	-	-
1855-1882	The Metropolitan Building Acts 1855 to 1882 (London, UK) [89]	-	-	-	-
	Laws, Codes and Guidelines – development				
1860	The Laws of New York State (US) [59] [1]	-	-	-	-
1862	The Laws of New York State (US) [60]	150[1] (75)	7.2 (3.6)	150[1] (75)	7.2 (3.6)

Year	Laws, Codes and Guidelines	Office building			
		Ground floor		Upper floor	
		psf	kN/m²	psf	kN/m²
1866	The Laws of New York State (US) [90]	150[1] (75)	7.2 (3.6)	150[1] (75)	7.2 (3.6)
1871	The Laws of New York State (US) [62]	150[1] (75)	7.2 (3.6)	150[1] (75)	7.2 (3.6)
1881	An Encyclopædia of Architecture: Historical, Theoretical, and Practical (London, UK) [12]	128[2] (100)	6.13 (4.8)	128[2] (100)	6.13 (4.8)
1886	The architect's and builder's pocket-book (NY, US) [13]	100[3] (40)	4.8 (1.9)	100[3] (40)	4.8 (1.9)
1891	The Laws of New York State (US) [14]	100[4] (70)	4.8 (3.35)	100[4] (70)	4.8 (3.35)
1894	The Laws of New York State (US) [5]	100	4.8	100	4.8
1894	The London Building Act 1894 (London, UK) [91]	-	-	-	-
1895	Hand-book of steel sections – Dorman, Long & CO. (London, UK) [63]	80	3.83	80	3.83
1895	Building Laws in Boston (US) [92]	100	4.8	100	4.8
1895	Building Laws in Chicago (US) [92]	70	3.35	70	3.35
1896	Building Laws in Buffalo (US) [92]	70	3.35	70	3.35
1897	Building Laws in St. Louis (US) [92]	150	7.2	70	3.35
1898	Building Laws in Denver (US) [92]	70	3.35	70	3.35
1899	A treatise on architecture and building construction – International Correspondence Schools (NY, USA) [64]	70	3.35	70	3.35
1899	Building Laws in New York (US) [92]	150	7.2	75	3.6
1900-1922	Building code requirements for 106 representative cities (average, US) [2]	114	4.46	69.7	3.34
1901	The Building Code of the City of New York (1899) (US) [67]	150	7.2	75	3.6
1903	Appleby's Illustrated Handbook of Machinery (NY, US) [65]	70-80	3.35 – 3.83	70-80	3.35 – 3.83
1905	The architect's and builder's pocket-book (NY, US) [66]	80	3.83	60	2.87
1905	National Building Code (US) [93]	150	7.2	75	3.6
1906	The Building Code of the City of New York (US) [94]	150	7.2	75	3.6
1909	The London Building Acts 1909 (London, UK) [68]	100	4.8	100	4.8
1923	Standard Specification for Structural Steel Buildings (UK) [95]	-	-	-	-
1925	Minimum live loads allowable for use in design of buildings: Report of Building Code Committee (NY, US) [2]	50	2.4	50	2.4
1927	Uniform Building Code – International Conference of Building Officials (CA, US) [96]	50[5]	2.4	50[5]	2.4
1927	Institution of Structural Engineers Report on Steelwork for Buildings (UK) [4]	100	4.8	80	3.8
1932	BS 449:1932 The use of structural steel in building (UK) [97]	80	3.8	50	2.4
1945	American standard building code (US) [98]	80	3.8	80	3.8

Year	Laws, Codes and Guidelines	Office building			
		Ground floor		Upper floor	
		psf	kN/m²	psf	kN/m²
1948	BS 449:1948 The use of structural steel in building (UK) [99]	50	2.4	50	2.4
1952	Code of functional requirements of buildings, Chapter V: Loading (UK) [100]	60	2.9	50	2.4
1956	ANSI A58.1-1955 American standard building code requirements for minimum design loads in buildings and other structures [101]	80	3.8	80	3.8
1963	Specification for the Design, Fabrication & Erection of Structural Steel for Buildings [102]	-	-	-	-
1969	Code of Basic Data for the Design of Buildings, CP3: Chapter V, Loading, Part 1: Dead and Imposed Loads (UK) [103]	52.2	2.5	52.2	2.5
1984	BS 6399-1:1984 Loading for buildings. Code of practice for dead and imposed loads (UK) [104]	-	2.5	-	2.5
1994	Uniform Building Code – International Conference of Building Officials (CA, USA) [105]	50[5]	2.4	50[5]	2.4
2005	NA to BS EN 1991-1-1:2002 UK National Annex to Eurocode 1: Actions on structures [69]	-	3.0	-	2.5
2013	ASCE 7:2013 Minimum Design Loads for Buildings and other Structures [72]	50	2.4	50	2.4
2014	BCO Guide to Specification – Best practice in the specification for offices (UK) [3]	-	3.0	-	2.5
2018	MEICON Global Floor loading codes for 64 countries (average) [11]		2.4		2.4

[1] 150 for stores, factory, warehouse, commercial; dwellings

[2] Dwellings

[3] 100psf storage of grain; 40psf dwellings

[4] House, Hotels; ordinary school-rooms and rooms for light mechanical purposes

[5] Provision shall be made in designing office floors for load of two thousand pounds upon any space two and one-half feet square wherever this load upon and otherwise unloaded floor would produce stresses greater than those caused by uniformly distributed load of fifty pounds per square foot

8 Salt storage calculations

Table 7: Storage calculation – salt storage in American Standard Barrels (ASB)

Storage of salt
American Standard Barrels (ASB)
180-200 litres / 50-53 US gallons, 40-44 imp gallons
Width: 21'' = 0.64m
Length (when lying): 34'' = 0.86m + 0.24 = 1.10 m
Area (when flat): 0.70 m²
Bulk sea salt: 1.35 kg/l
Barrel weight with salt per square metre: (251lbs + 850lbs)/m² = 1101lbs/m² = **102 psf** = **4.9 kN/m²**

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