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FEM R&S Technical Report TR01

Reliability of the structural safety based upon EN1990 – Pallet racking: Design in accordance with EN15512:2009 / prEN:15512:2018.

Part 1: General approach, Definition of Variables and Conclusions

Part 2: Probabilistic reliability approach to determine load- and material factor

Part 1: General approach, Definition of Variables and Conclusions

Contents

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1 Goal of the initiative and conclusions

The Sub-Working group "Structural Reliability of Racks Designed According to EN 15512" of CEN/TC344-WG1 was set up in order to clarify:

- the level of reliability against structural failure (ULS) is complying with EN 1990 and/or recommended by relevant guidelines/publications for structures comparable to steel storage racks
- whether the partial safety factors given in the EN 15512:2009 lead to a structural reliability of pallet racks falling into this range of recommended values

It is concluded for RC2 that the following partial safety factors - as given in prEN 15512:2018 and when applied in combination with the design methods of the same standard - would meet the structural reliability requirements of EN 1990:

- γ_F = 1.4 for storage loads when weights are not monitored
- γ_F = 1.3 for storage loads when weights are monitored (controlled) and rejected when the weight is not complying with the project specification
- γ_M = 1.1 for steel members

If the limit value of the slab deformation due to the rack loading given in prEN 15512:2018 is not exceeded, it can be ignored in the design of the racks in case of bolted upright frames. Whereas slab deformation must always be taken into account in the design in case of welded frames.

Note Safety factors, as for connection elements, live loads, serviceability limit states etc, are not dealt with in this report.

2 Method of analysis

In order to evaluate the structural reliability of steel storage racks designed according to EN 15512:2009 semi-probabilistic analyses are carried out in compliance with EN 1990 applying all variables on the action side as statistical distributions which are combined to a resulting single statistical distribution reflecting the effect of all relevant actions by so called "limit state functions". With this procedure, the reliability of the racks against structural failure is determined and compared with values recommended in relevant guidelines / publications.

A set of analyses is conducted to cover the governing structural elements and different conditions within the storage facility: Consequently, calculations are done for the beam design as well as for the upright design, considering uncontrolled and controlled weight of the storage load and assuming the frame bracing to being bolted as well as being welded to the upright.

3 Data and boundary conditions

The following table summarises the variables and boundary conditions used as the basis for the probabilistic analysis:

Data / boundary condition	Explanation / remark
Storage load	The statistical parameters of the storage load are derived from recorded data of a warehouse. A comparison with load data of other warehouses shows that the data used for this study have a scatter which is two times greater. Therefore, it can be assumed that the data set is conservative. Another important step is the transformation of the load records into yearly extreme values without setting an upper bound value which again can be assumed to be a conservative procedure.
Dead load of the structure	The dead load of the structure plays a minor role compared to the influence of the storage load and may be ignored in the context of this reliability study.
Placement load (horizontal + vertical / manually and crane operated)	Instead of applying the vertical placement load according to the rules given in EN 15512:2009 the dynamic load effects for fork lift truck operated racks are determined from testing and for fully automated racks from specifications of the Storage/Retrieval machinery suppliers.
Model uncertainty	Inaccuracies of the calculation model are considered by a statistical distribution which is in line with definitions in scientific literature.
Effect of damaged uprights	The probabilistic simulation assumes that 5 % of the uprights are affected by the maximum permissible damage according to the green level of EN 15635; this leads to a 20 % reduction of the bearing capacity. In the calculation this is considered by enhancing the axial load by a factor of 1.2 with a probability of 5 %. The 20 % load enhancement due to damaged uprights is also applied to the pallet beams (probability of occurrence 5 %).
Frame shear stiffness	The values for the frame shear stiffness are obtained from test reports. Consequently, different values are applied for bolted and welded rack frames.
Frame imperfections	For the installation tolerances (or the permissible initial out of plumb) the limit values according to EN 15620:2008 are applied.
Rotation of the floor slab	Floor slab deformation results in increased axial forces in the uprights etc. Resulting from a discussion based on the views of different experts a rotation of 1/625 is applied.
Eccentricities of the beam and upright frame bracing connections	A parametric study shows that the effect of the eccentricities with regard to the centre line of the upright section is negligible compared to other influence factors provided that the limit values defined in EN 15512:2009 are not exceeded and the frames are not subjected to wind or seismic loads.
Eccentricity of the centre of gravity of the stored goods on a pallet	(Unplanned) eccentric loads on pallets lead to unequal beam and upright loading. This is described by a statistical distribution.

4 Development process and approval

The SUB WG started their activities in 2016, one year after the start of the CEN process. Document CEN-TC344-WG1_N0081 [3] was the starting point. Two years later TNO reviewed and approved version V1e of May 2018. TNO requested some improvements and additions. The procedures applied and the results obtained are supported by TNO, see Figure 1. TNO focussed on the methodology and not on the statistic distributions. The distributions are discussed and approved by the SUB WG.

The TNO approved version of 2018 showed that the dynamic effect for a single pallet compartment in the design standard should be increased from 25% to 70%. This is also stated in prEN 15512:2018. This increase seemed unrealistic. The dynamic effect used in the Monte Carlo study of 2018 was based on an analytical model, verified with a test on a 3 pallet per compartment configuration. To verify the dynamic effect for a single pallet compartment configuration, additional tests were performed in 2019. These new tests showed that the dynamic effect for a single pallet compartment is significantly lower compared to the analytical approach.

This updated report reflects the results of these tests. The addition study showed that the 25% of the 2009 version was realistic. In addition, the statistical distribution for the vertical placement speed is discussed and modified (see 9.4.4 and 9.7). Since only parameters were modified and not the methodology, a new approval of TNO is superfluous.

TNO innovation for life

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Copy to
Ir. Jan Willem Frederiks (Nedcon)

Subject
Review calibration study pallet racking EN 15512:2018

Dear Mr Hommes,

Based on a review of the Nedcon report "Reliability design according to EN 1990 for adjustable pallet racking - Version V1e, 2018-May", TNO concludes that the performed calibration of the partial factor of the EN 15512:2018 has been done in line with the principles of the reliability philosophy of the Eurocodes.

As part of the review process, the principles of the actual calibration process were discussed and stated by the authors of the Nedcon report (Dr.-Ing. Oliver Kraus, Ir. Jan Willem Frederiks and Bsc. Jeroen Hermsen) and the reviewers of TNO (Ir. Nadieh Meinen and Dr.Ir. IJsbrand van Straalen). Based on these principles, the calibration of the partial factors was finalized by Ir. Jan Willem Frederiks and Bsc. Jeroen Hermsen and they also prepared a draft version of the Nedcon report. This draft version was reviewed by Ir. Nadieh Meinen and Dr.Ir. IJsbrand van Straalen and the results of this reviewed were discussed. Based on the findings of the review, the final version of the Nedcon report was prepared.

In addition to the review TNO also prepared a proposal for a text to be added as the Dutch A-deviation "Dutch National Legislative Deviations" to the EN 15512:2018. Two versions are given below.

Compact version:

> In The Netherlands racking and shelving and therefor adjustable pallet racking is, apart from work equipment, also to be considered as "structure other than a building" according to the Building Decree 2012. The structural safety of adjustable pallet racking considering its specified use, shall comply with EN 15512. The requirements and verification methods given by EN 15512 have an equivalent provision to NEN-EN 1990, NEN-EN 1993-1-1 and their National Annexes.

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Date
11 June 2018

Our reference
100314936/SNY/hns

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Extended version, including reference to the Dutch regulation:

In The Netherlands racking and shelving and therefor adjustable pallet racking is, apart from work equipment, also to be considered as "structure other than a building" according to the Building Decree 2012 (Stb. 2011: 416, 676; Stb. 2012: 125, 256, 441, 643; Stb. 2013: 75, 244, 462; Stb. 2014: 51, 211, 232, 233; 333, 342, 358, 539; Stb 2015: 92, 249, 425, Stb 2016: 383, 384, Stb. 2017: 268, 324, 494). The structural safety of adjustable pallet racking considering its specified use, shall comply with EN 15512. The requirements and verification methods given by EN 15512 have an equivalent provision to NEN-EN 1990+A1+A1/C2:2011, NEN-EN 1990+A1+A1/C2/NB:2011, NEN-EN 1993-1-1+C2+A1:2016 and NEN-EN 1993-1-1+C2+A1/NB:2016.

With kind regards,

Dr.Ir. IJsbrand van Straalen

Figure 1 – Letter TNO

Part 2: Probabilistic reliability approach to determine load- and material factor

Contents

5 Introduction

Part 2 of this technical report compares the design methods of the design standard EN 15512:2009 with a statistical evaluation of load effects (Monte Carlo). The calibration process of adjusting the design procedure leads to the required target reliability as defined in EN 1990.

6 List of acronyms

UDL uniformly distributed load

PL concentrated load

UL unit load

V_{pl} vertical placement load

H_{pl} horizontal placement load

H_{cr} horizontal crane load

V_{sd} Minimum design shear force in frame

UT uncertainty tolerance

GL green level

CDF cumulative distribution function

PDF Probability density function

GEV generalized extreme value

APR Adjustable pallet racking

MLE Maximum likelihood estimation

7 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 528, Rail dependent storage and retrieval equipment Safety

EN 1990, Eurocode Basis of structural design EN 1991-1-1:2002, Eurocode 1: Actions on structures General actions

EN 1993-1-1:2005, Eurocode 3: Design of steel structures Part 1-1: General rules and rules for buildings

EN 1993-1-3:2006, Eurocode 3: Design of steel structures Part 1-3: General rules

EN 10143, Continuously hot-dipped coated steel sheet and strip - Tolerances on dimensions and shape

EN 10162, Cold rolled steel sections Technical delivery conditions Dimensional and cross-sectional tolerances

EN 10346, Continuously coated hot-dip coated steel flat products Technical delivery conditions

EN 15620, Steel static storage systems Adjustable pallet racking Tolerances, deformations and clearances

EN 15629, Steel static storage systems The specification of storage equipment

EN 15635, Steel static storage systems The application and maintenance of storage equipment

EN 15878, Steel static storage systems Terms and definitions

EN ISO 6892-1, Metallic materials Tensile testing Part 1: Method of test at room temperature

EN ISO 7438, Metallic materials Bend test EN ISO 9001, Quality management systems Requirements (ISO 9001:2000)

ETAG No 001, Guideline for European Technical Approval of Metal Anchors for Use in Concrete

JCSS 2001, JCSS Probabilistic model code part 3: Resistance Models

8 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

4.1
accidental action
action, usually of short duration but of significant magnitude, that is unlikely to occur on a given structure during the design working life

4.2
basic material
flat steel sheets or coiled strip, possibly cold-reduced from which the rack components are pressed or rolled

4.3
batch
quantity of material, all to the same specification, produced by one supplier at one time

4.4
beam
horizontal member linking adjacent frames and lying in the horizontal direction parallel to the operating aisle

4.5
beam end connector
connector, welded to, bolted to, or otherwise connected or formed as an integral part of the beams, which has hooks or other devices which engage in holes or slots in the upright

4.6
compartment load
load which can be loaded into one compartment of a rack structure from one side

4.7
double entry rack
run of racking accessible from two adjacent operating aisles connected by run spacers

4.8
global analysis
determination of a consistent set of internal forces, moments and displacements that represent the entire three dimensional load bearing rack structure, which are in equilibrium with a particular set of actions on the structure

4.9
placement load
load caused by deposit and picking operations of a unit load into and out of the system, reflecting good practice

4.10
quasi-rigid
conceptual term allowing the assumption of full rigidity of the floor slab

4.11
single entry rack
run of racking accessible from a single operating aisle

4.12
spine bracing
sway bracing in the vertical plane parallel to the main aisle of the rack, linking adjacent frames

4.13
sway
horizontal displacement of structure in addition to any initial out-of-plumb

4.14
buckling length
system length of an otherwise similar member with pinned ends, which has the same critical buckling load as a given member or segment of member

4.15
system length
distance in a given plane between two adjacent points at which a member is braced against lateral displacement and/or torsion in this plane, or between one such point and the end of the member

4.16
design working life
assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance

4.17
unit load
individual item which can be placed or retrieved in one operation, e.g. a pallet or a container with goods in a racking system

4.18
un-stiffened element
part of the cross-section which is connected to the remainder of the section along one longitudinal edge only

4.19
upright frame
two or more upright sections linked together by means of a lattice and fitted with base plates intended to support the storage levels and provide stability in the cross-aisle direction. Typical examples are shown in Figure 2.

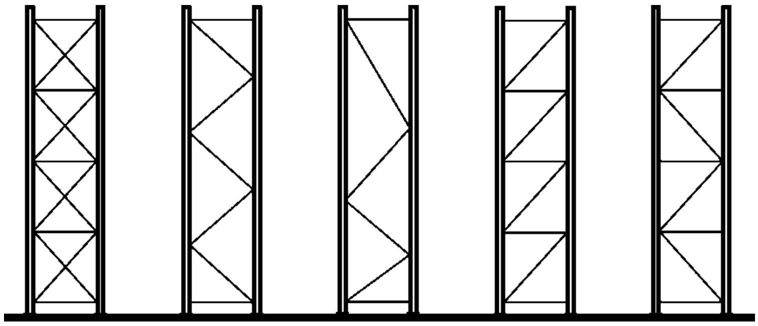


Figure 2 - Typical forms of upright frames

4.20
supporting floor of the racking
foundation of the racking. For example a ground bearing, pile supported or suspended slab.

4.21
gross section properties
the properties of the section without any consideration for perforations, local buckling, distortional buckling or effects of cold-forming.

4.22
perforated member
member with multiple holes regularly spaced along its length

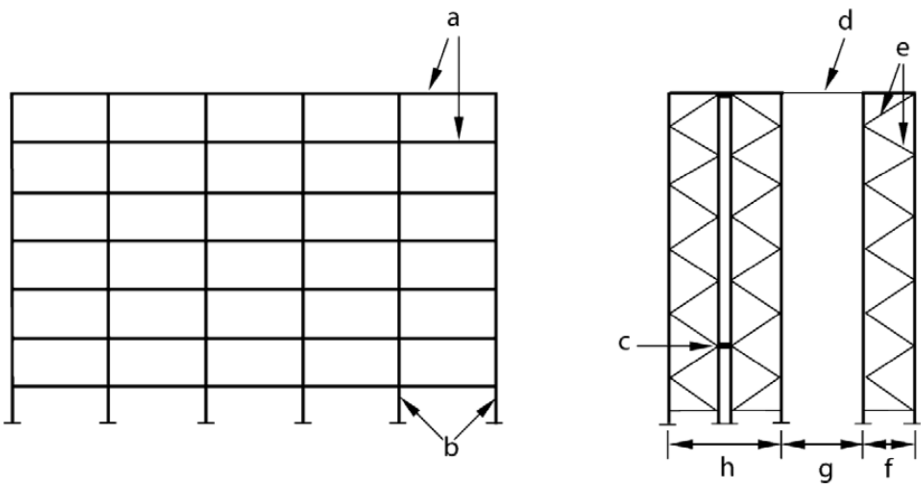
4.23
minimum section properties
the properties of a perforated element corresponding to the gross cross-section with the maximum reduction for the effect of the perforations.

4.24
effective section properties
the properties for strength are the section properties taking account of the effects of perforation, buckling (local, distortional) and effects of cold-forming.

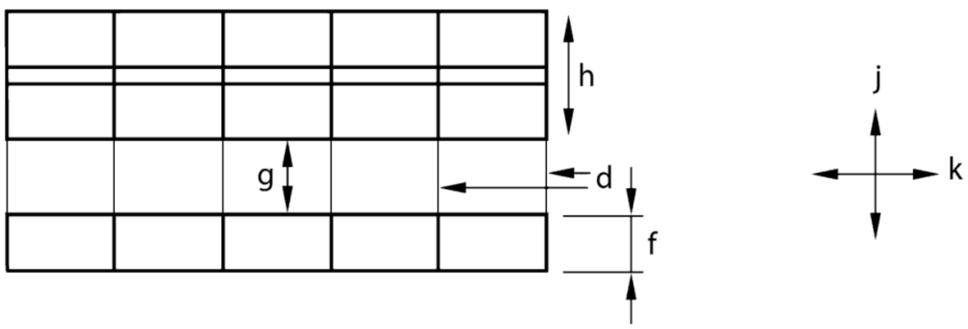
4.25
equivalent section properties
the properties of an element corresponding to the cross-section stiffness behaviour taking into account perforations.

4.26
regular rack
rack with components (beam, uprights, etc.) of the same type, length and vertical spacing. A rack where the distance from the ground to the first beam level is different to the remainder may be considered as regular.

4.27
un-braced racking systems
rack in which the down-aisle stability is provided by restraining effect of the beam-end connectors and not by spine bracing (typical un-braced pallet rack is shown in Figure 3).



Side view



Plan view

Key

a beams

b upright frames

c run spacers

d top tie (when required)

e frame bracing

f single entry rack

g aisle

h double entry rack

j cross-aisle

k down-aisle

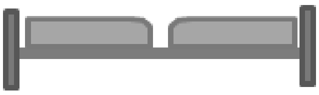
Figure 3 - Example of an un-braced pallet racking structure

9 Reliability design beams

9.1 Introduction

The target reliability as defined in EN 1990 is analysed for the beams, using a probabilistic approach, for the following unit load configurations (see Table 1).

Table 1 - Overview of load units per compartment

Number of load units per compartment:		
Single load	**Two loads**	**Three loads**
		

The load effects taken into account in the reliability design are explained and their distributions are discussed. The results of the Monte Carlo simulation are used to determine the correction factor (γ_{cor}) in order to meet the target reliability.

9.2 Reliability classes

Table 2 – Consequence classes according to EN 1990

Consequences Class	Description	Examples of buildings and civil engineering works
CC3	**High** consequence for loss of human life, *or* economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)
CC1	**Low** consequence for loss of human life, *and* economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses

Table 3 – Reliability classes according to EN 1990

Reliability Class	**Minimum values for β**	
	1 year reference period	**50 years reference period**
RC3	5,2	4,3
RC2	4,7	3,8
RC1	4,2	3,3

Pallet racking systems can be classified in consequence class CC2 (see Table 2) and Reliability Class RC2 (see Table 3). For a 1 year reference period this leads to $\beta \geq 4.7$.

This means a probability of failure of ≈ 1/25.000 in a life time of 30 years and a probability of failure of ≈ 1/15.000 in a life time of 50 years.

The safety philosophy of EN 15512 is based on reliability class RC2. Therefore, this report focusses on RC2. To be complete also the reliability for RC1 and RC3 is studied.

For RC1 $\beta \geq 4.2$ for a 1 year reference period.

For RC3 $\beta \geq 5.2$ for a 1 year reference period.

9.3 Cases

In order to get a reliable recommendation, sufficient cases need to be considered. In total 36 cases are defined to reflect the scope of EN15512. These cases are considered to cover every possible configuration used in the racking industry.

- Q_p
  - 4 and 13.5 kN
- number of UL's / compartment
  - 1,2 and 3
- Maximum allowable beam deflection mentioned in EN15620
  - L/200 and L/300

Note: For manual operated racking only L/200 is mentioned in EN 15620

- type of operation
  - manual operated warehouse
  - automatically operated warehouse
- weight control and refusal
  - checked and not checked

Combining these influences leads to 36 cases. These cases are listed in Table 4 and Table 5.

The first 24 cases have no weight check of the unit load and the last 12 cases have a weight check and refusal system. This system will reduce the mean and standard deviation off the monthly extremes, see Table 10.

Table 4 - Cases when pallet load is not checked

			pallets per compartment	Q_p	L	stiffness requirement	Operation
		Case	n	(kN)	(mm)	L/	
No weight check	Manually operated	1	1	4	950	200	MAN
		2	1	13.5	950	200	MAN
		3	1	4	950	300	MAN
		4	1	13.5	950	300	MAN
	Automatically operated	5	1	4	950	200	AUT
		6	1	13.5	950	200	AUT
		7	1	4	950	300	AUT
		8	1	13.5	950	300	AUT
	Manually operated	9	2	4	1825	200	MAN
		10	2	13.5	1825	200	MAN
		11	2	4	1825	300	MAN
		12	2	13.5	1825	300	MAN
	Automatically operated	13	2	4	1825	200	AUT
		14	2	13.5	1825	200	AUT
		15	2	4	1825	300	AUT
		16	2	13.5	1825	300	AUT
	Manually operated	17	3	4	2700	200	MAN
		18	3	13.5	2700	200	MAN
		19	3	4	2700	300	MAN
		20	3	13.5	2700	300	MAN
	Automatically operated	21	3	4	2700	200	AUT
		22	3	13.5	2700	200	AUT
		23	3	4	2700	300	AUT
		24	3	13.5	2700	300	AUT

Table 5 - Cases when pallet load is checked and refused when too heavy

			pallets per compartment	Q_p	L	stiffness requirement	Operation
		Case	n	(kN)	(mm)	L/	
Weight check	Automatically operated - weight check	25	1	4	950	200	AUT - W
		26	1	13.5	950	200	AUT - W
		27	1	4	950	300	AUT - W
		28	1	13.5	950	300	AUT - W
		29	2	4	1825	200	AUT - W
		30	2	13.5	1825	200	AUT - W
		31	2	4	1825	300	AUT - W
		32	2	13.5	1825	300	AUT - W
		33	3	4	2700	200	AUT - W
		34	3	13.5	2700	200	AUT - W
		35	3	4	2700	300	AUT - W
		36	3	13.5	2700	300	AUT - W

9.4 Load effects

The load effects that were taken into account in the Monte Carlo analysis are discussed in this section.

9.4.1 Pallet load

9.4.1.1 general

To obtain a conservative probability distribution for the pallet load effect, a large data set from a large warehouse is analysed. This warehouse is from a convenience store and therefore has a wide variety of products stored in its warehouse. Due to this wide variety it is assumed that this warehouse is conservative and representative for all of Europe. These mixed goods pallets are weighted, and over the course of four years, a total 73118 pallet data was recorded. By recording the pallet data for 4 years and 4 seasons a reliable data set was obtained. It is important to note that the specified upper bound value for the pallet weight (Qp) is 1350 kg and that the pallets are not rejected in case of an overload.

The pallet data not only consists of weights but also have a time variant, this way monthly extremes can be extracted from the data. These monthly extremes can be found in Table 6.

Table 6 - Data points of monthly extremes μ = 1022.7, σ = 200

Monthly extremes in pallet weight[kg]			
622	897	1026	1160
683	910	1038	1175
720	926	1049	1191
754	939	1062	1209
777	950	1075	1224
801	960	1085	1248
819	971	1097	1266
836	983	1112	1292
854	994	1123	1323
869	1004	1134	1364
885	1017	1150	1426
1325	1325	700	741

To extrapolate monthly extremes to yearly extremes a distribution can be fitted onto these monthly extremes. A GEV (generalized extreme value) distribution is fitted onto the 48 data points using a maximum likelihood estimation. The choice for a generalized extreme value distribution is based on engineering judgement; the specified maximum load for a unit load (pallet) is an upper bound value. Other upper bound tail behaviour from, for example, a log normal distribution would not be representative. The parameters for the generalized extreme value distribution fitted to the monthly extremes can be found in Table 7. The fitting is done with a maximum likelihood estimation. A visualization of a normalized histogram and PDF of the GEV can be found in Figure 4.

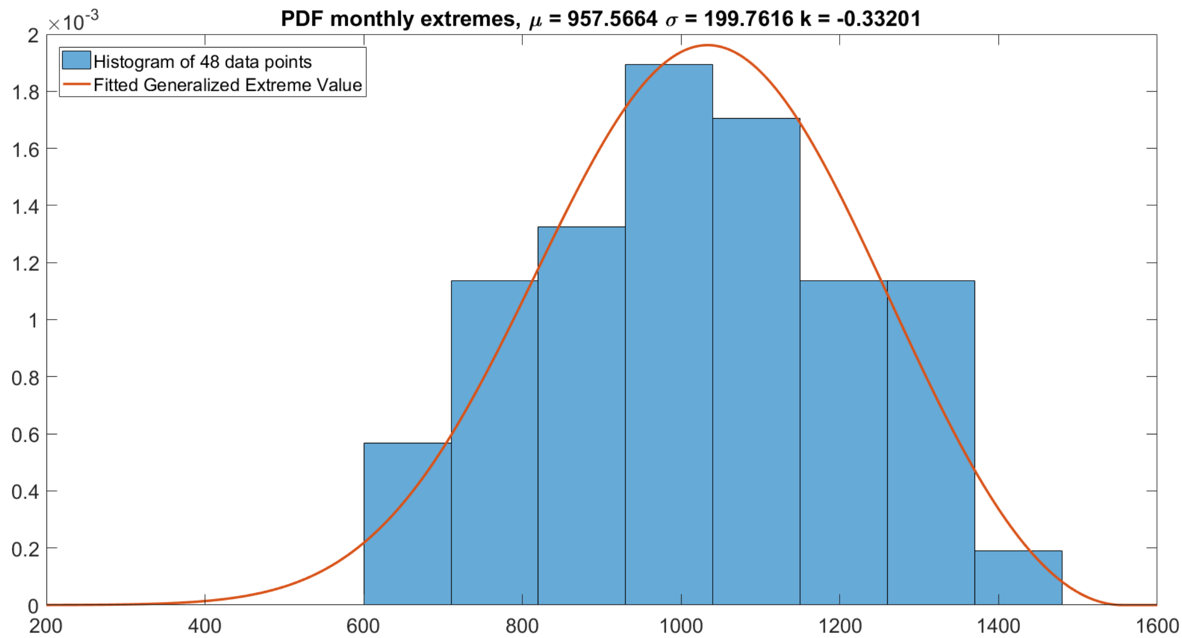


Figure 4 - Histogram of the data and PDF of the fitted GEV

Table 7 - GEV parameters and 95% confidence interval

GEV parameters		95% confidence interval	
k=	-0.33201	-0.558275	-0.105745
sigma =	199.762	157.713	253.021
mu =	957.566	893.98	1021.15

In the Monte Carlo analysis an additional case with low pallet loads of Q_p = 400 kg is used. This is done because some effects have a higher contribution when lower pallet weights are being used. To scale down from a Q = 1350 kg to a Q = 400 kg a factor of 400/1350 = 8/27 is used. This is applied to the GEV parameters to acquire a distribution for lower pallet weights.

The used GEV has a CDF and with the help of this CDF the cumulative probability of the monthly extremes can be transformed to the cumulative probability of the yearly extremes. This can be done following equation (1).

$$F_{X,T2}(x) = [F_{X,T1}(X)]^{T2/T1} \tag{1}$$

Resulting in the equations for the PDF and CDF of the yearly extremes, see Table 8. These equations can be plotted to give a visual representation of the situation. These figures can be seen in Table 9.

Table 8 - Equations of the monthly and yearly PDF and CDF

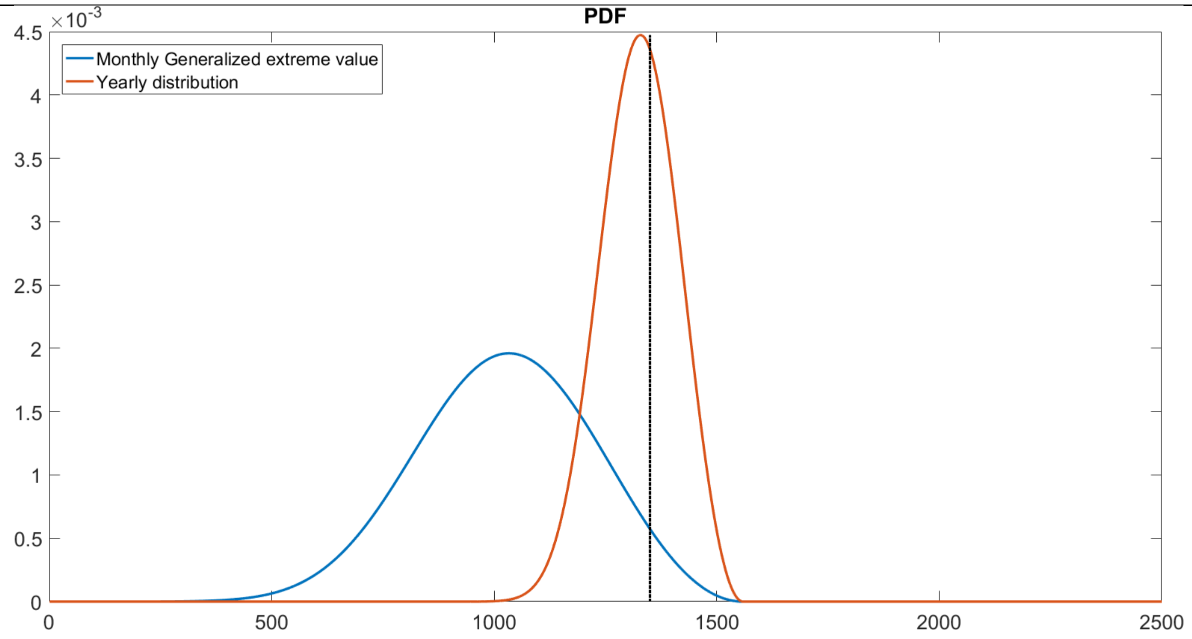
Monthly	Yearly
$PDF_{mon} = \frac{e^{-\frac{1}{\left(1-\frac{k(\mu-x)}{\sigma}\right)^{\frac{1}{k}}}}}{\sigma\left(1-\frac{k(\mu-x)}{\sigma}\right)^{\frac{1}{k}+1}}$	$PDF_{year} = \frac{12\, e^{-\frac{12}{\left(1-\frac{k(\mu-x)}{\sigma}\right)^{\frac{1}{k}}}}}{\sigma\left(1-\frac{k(\mu-x)}{\sigma}\right)^{\frac{1}{k}+1}}$
$CDF_{mon} = e^{-\frac{1}{\left(1-\frac{k(\mu-x)}{\sigma}\right)^{\frac{1}{k}}}}$	$CDF_{year} = e^{-\frac{12}{\left(1-\frac{k(\mu-x)}{\sigma}\right)^{\frac{1}{k}}}}$

9.4.1.2 Pallet load for systems with weight check and rejection

The accuracy of the weighing systems is approximated at 5% (see FEM 9.841). In practice the weighing device has at least a 5% accuracy. If Q_p= 1350 kg this will means that a UL with a weight higher than 1.05 · 1350 = 1418 kg is rejected. This transforms the CDF and PDF of the weight checked distributions. The new PDF and CDF can be found in Table 10.

Table 9 - CDF and PDF of monthly GEV extremes and yearly distribution extremes

probability density function



Cumulative distribution function

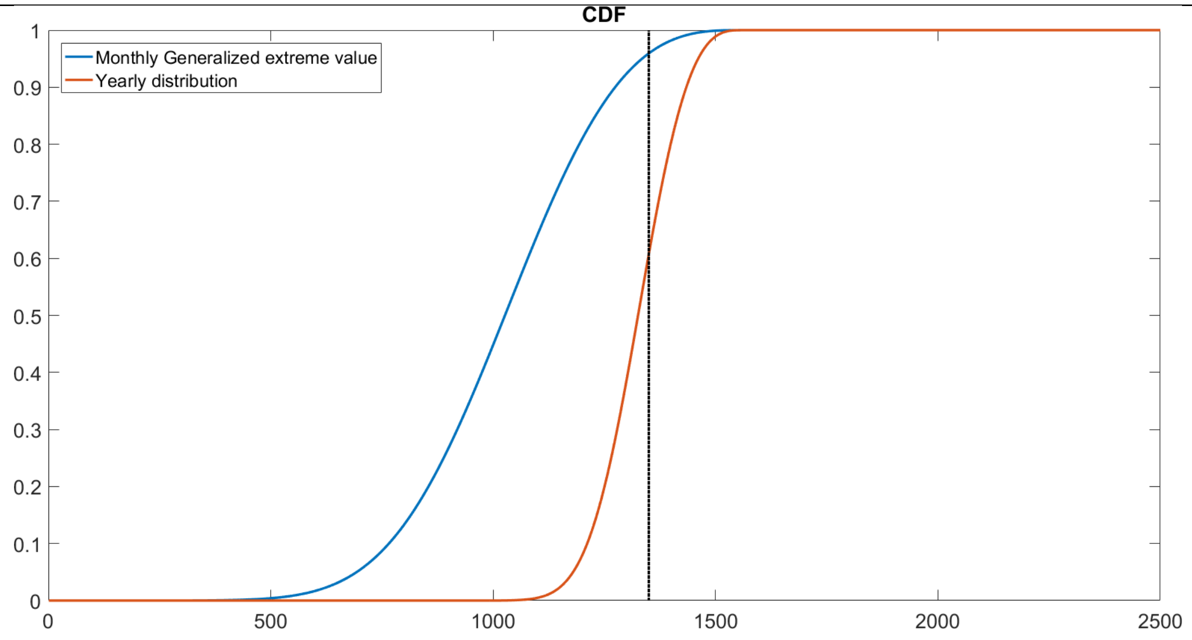
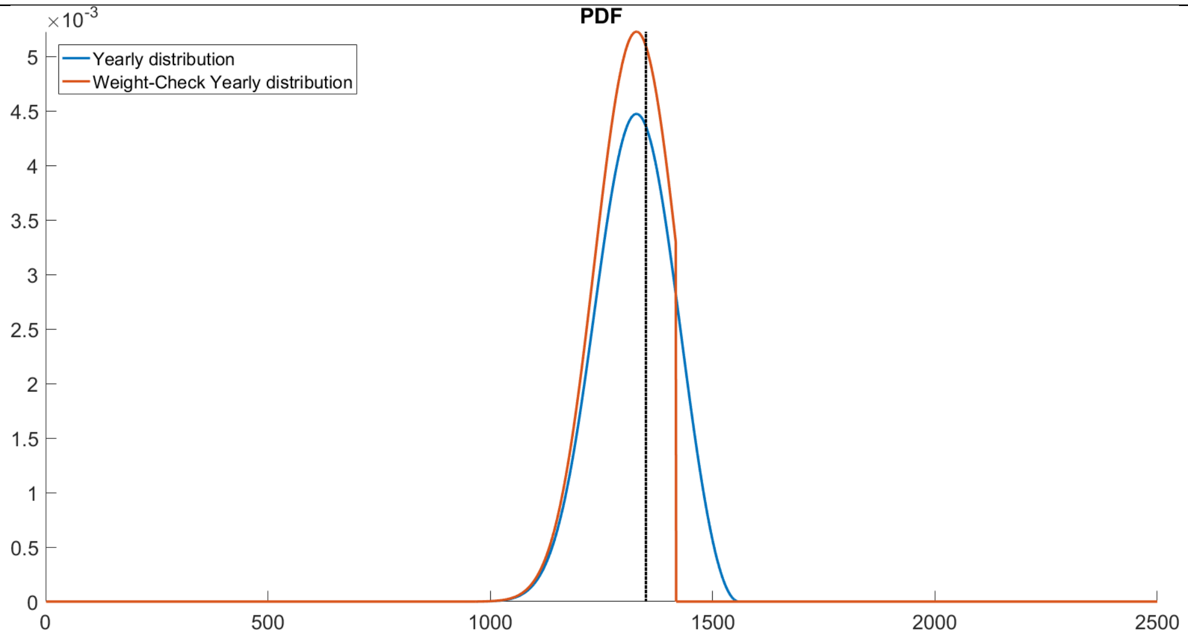
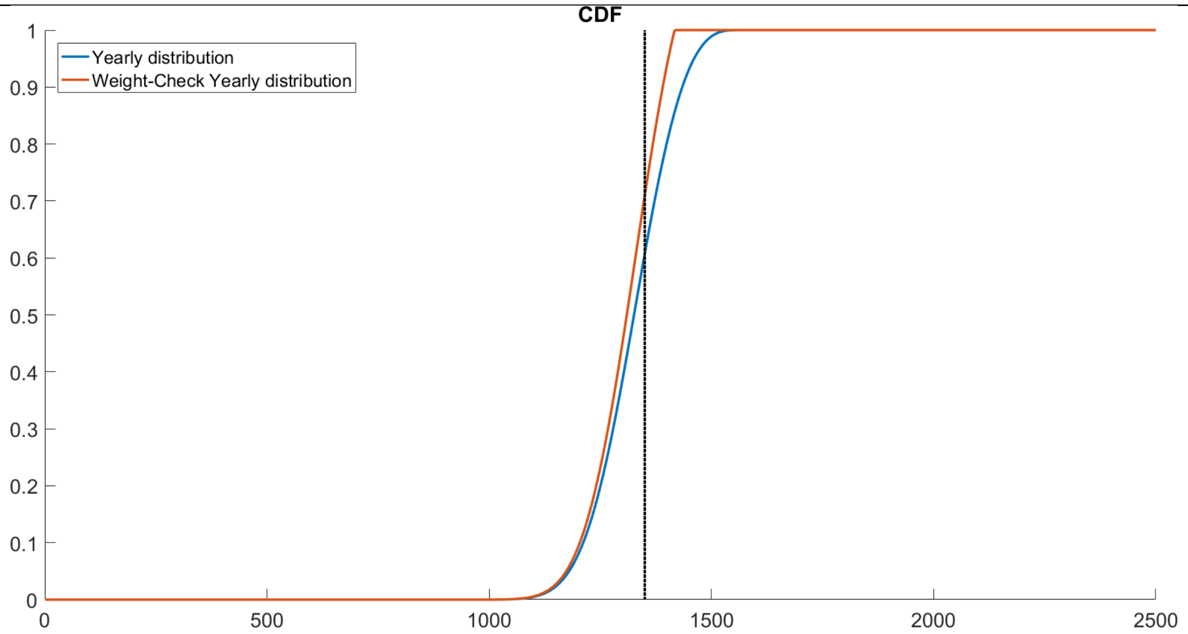
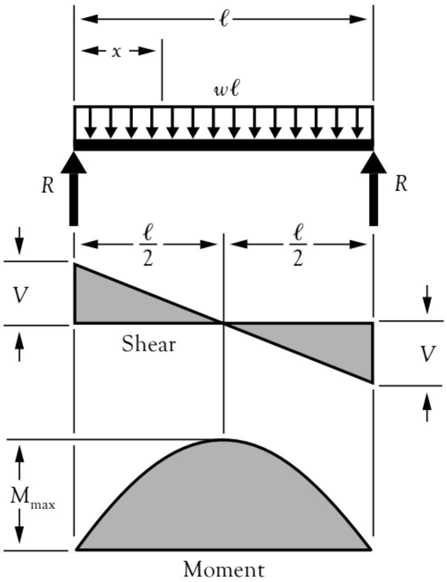


Table 10 - CDF and PDF of yearly distribution without and with weight check

probability density function

Cumulative distribution function


9.4.2 Influence factor for unit load

When there are three loads placed in one compartment the middle UL will have a higher effect on the bending moment of the beam. Therefore, each UL will get its own influence factor. See Table 11.



$$R = V \quad \dots\dots\dots\dots \quad = \frac{w\ell}{2}$$

$$V_x \quad \dots\dots\dots\dots \quad = w\left(\frac{\ell}{2} - x\right)$$

$$M_{max} \text{ (at center)} \quad \dots\dots\dots \quad = \frac{w\ell^2}{8}$$

$$M_x \quad \dots\dots\dots\dots \quad = \frac{wx}{2}(\ell - x)$$

$$\Delta_{max} \text{ (at center)} \quad \dots\dots\dots \quad = \frac{5w\ell^4}{384\,EI}$$

$$\Delta_x \quad \dots\dots\dots\dots \quad = \frac{wx}{24\,EI}(\ell^3 - 2\ell x^2 + x^3)$$

Figure 5 - Moment line for uniformly distributed load

For a single and two pallet loads per compartment the bending moment caused by each load can easily be seen. Due to symmetry the two loads will cause the same bending moment as each other. This can be seen in Table 11. For three loads an integral needs to be calculated. The equations from Figure 5 are used. The bending moment for the left load is calculated in equation 3, due to symmetry the bending moment of the right load is equal. The resulting bending moment is caused by the middle load.

Table 11 - Overview of Influence factors per UL for maximum moment

Influence factors per UL for maximum moment:		
Single load	**Two loads**	**Three loads**
1	0.5 / 0.5	0.26 / 0.48 / 0.26

$$M_{tot} = \int_0^l M_x dx = \int_0^l (-\frac{W}{2}x^2 + \frac{WL}{2}x)dx$$
$$M_{tot} = \left[-\frac{1}{3}\frac{W}{2}x^3 + \frac{1}{2}\frac{WL}{2}x^2\right]_0^l = \frac{WL^3}{12}$$

(2)

$$M_{Left/Right} = \int_0^{\frac{1}{3}l} M_x dx = \int_0^{\frac{1}{3}l} (-\frac{W}{2}x^2 + \frac{WL}{2}x)dx$$
$$M_{Left/Right} = \left[-\frac{1}{3}\frac{W}{2}x^3 + \frac{1}{2}\frac{WL}{2}x^2\right]_0^{\frac{1}{3}l} = \frac{7\,WL^3}{324} \qquad (3)$$

$$\frac{M_{Left/Right}}{M_{tot}} = \frac{7}{27} \approx 0.26$$
(4)

9.4.3 Unit load placement eccentricity and center of gravity eccentricity

9.4.3.1 Design procedure EN 15512:2009

According to the design procedure of EN 15512:2009, 6.3.2 the unit load placement eccentricity needs to be considered when the effect is more than 12%. For this reason no center of gravity eccentricity is considered.

9.4.3.2 Monte Carlo load effect

In manually operated APR the placement eccentricity of multiple load units is not independent. The operator will use the adjacent load units for orientation. Therefore, only one function is taken for all unit loads. The function for the shift of centroid is considered random and therefore per unit load. A large exceedance of this shift of centroid is prevented by the EN15629. For an overview see Figure 6.

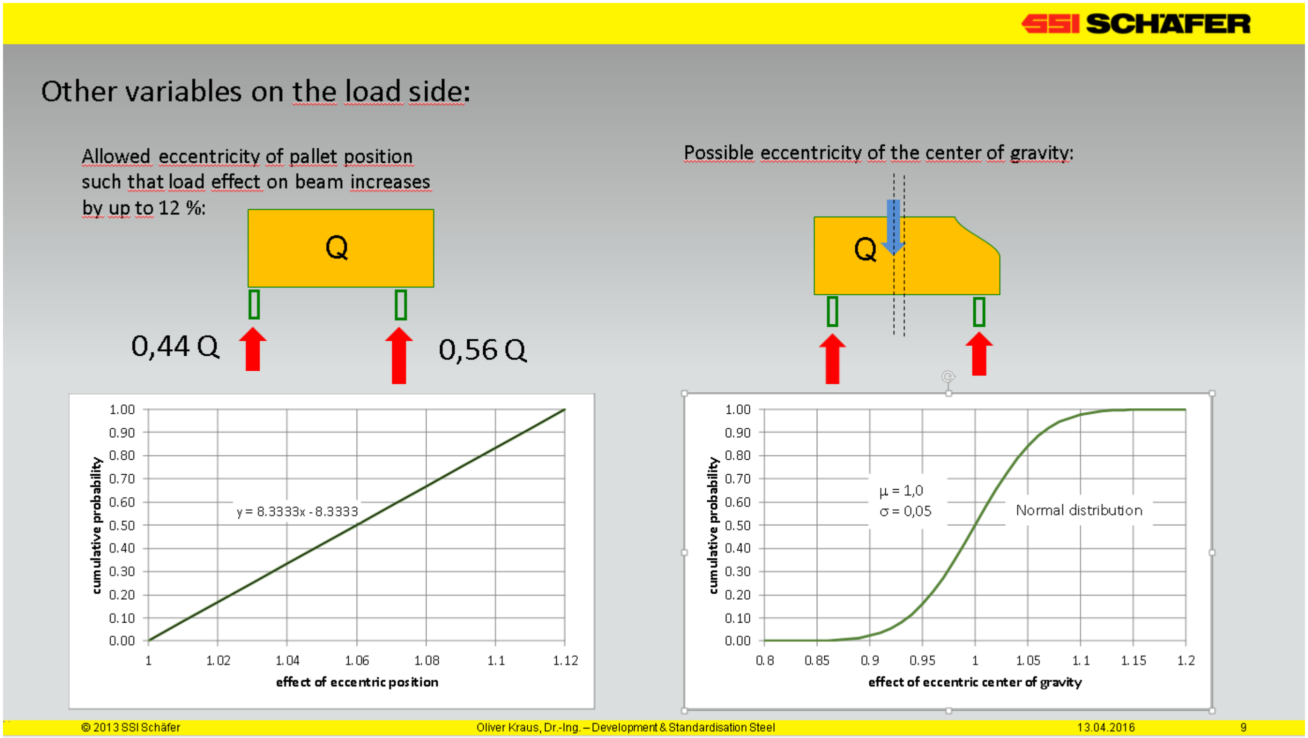


Figure 6 - Slide take from [3]

9.4.4 Vertical placement load

9.4.4.1 Design procedure EN 15512:2009

The vertical placement loads needs to be considered in case of a single load system or handling of multiple UL simultaneously (EN 15512:2009 - 6.3.3). An additional load of 25% of Q is used.

9.4.4.2 Monte Carlo load effect

The placing of a pallet will cause a dynamic amplification factor. For this dynamic amplification factor the minimum stiffness of the beam needed to reach the maximum allowable deflection are used. Calculations for this dynamic amplification factor ($\beta_{dynamic}$) can be found in Annex A.

9.4.4.2.1 Depositing speeds

The placement speed for manual and automatic systems are determined. The automatic placing is controlled. Schaefer uses a vertical placing speed for automated systems of 8 cm/s. A speed of 10 cm/s is adopted. During a CEN/TC344-WG1 meeting at TU Dortmund it is decided that a manual placing speed of 15 cm/s is a realistic upper bound for depositing in accordance with EN 15635. Because the automatic placing is controlled the standard deviation for the automatic placing is chosen lower than the standard deviation of the manual operated system. For an overview see Table 12.

Table 12 - Speed distribution parameters

	V (m/s)	
Operation	**μ**	**σ**
Manual	0.15	0.0375
Automated	0.1	0.0125

9.4.5 Effect UDL instead of concentrated loads

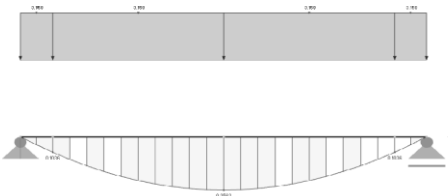
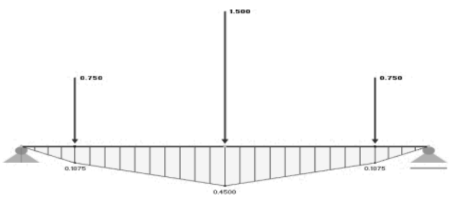
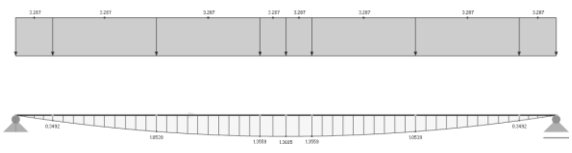
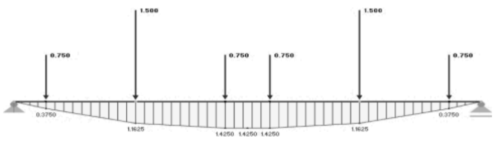
9.4.5.1 Design procedure EN 15512:2009

EN 15512:2009, 9.4.2 states: "It is usual to consider the loading on the beams to be uniformly distributed unless specified otherwise". This leads to an underestimation of the bending moment.

9.4.5.2 Monte Carlo load effect

How the weight of a pallet is distributed to the beam depends on many factors. A realistic assumption is to dived the load into three concentrated loads; respectively 25%, 50% and 25% (see Figure 10). This causes an enhancement of the bending moment. This load effect can be found in Table 13 and the enhancement factor can be found in Table 14.

Table 13 - Maximum bending moment for UDL and Concentrated loads

<table>
<tr><th colspan="2">One pallet per pair of beams</th></tr>
<tr><td></td><td></td></tr>
<tr><td>UDL = 1.3685</td><td>Concentrated loads = 1.4250</td></tr>
<tr><th colspan="2">Two pallets per pair of beams</th></tr>
<tr><td></td><td></td></tr>
</table>

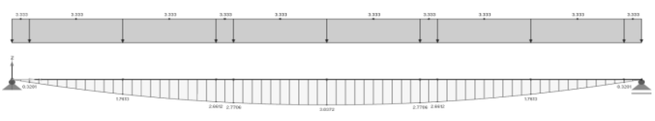
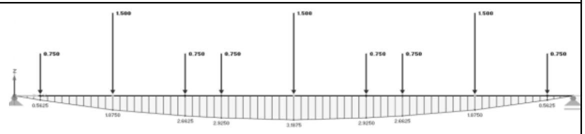
UDL = 1.3685	Concentrated loads = 1.4250
Three pallets per pair of beams	
	
UDL = 3.0372	Concentrated loads = 3.1875

Table 14 – Comparison of UDL and PL

# Pallets	UDL	PL	F
1	0.3563	0.4500	1.2630
2	1.3685	1.4250	1.0413
3	3.0372	3.1875	1.0495

9.4.6 Green level

9.4.6.1 Design procedure EN 15512:2009

No damage is considered.

9.4.6.2 Monte Carlo load effect

According to EN 15635 a minor damage GL is allowed. Orange and red levels of damage need repair.

Green level damage can lead to a capacity reduction of the upright up to 20%. For the beam design the same influence is adopted. It is assumed that there is a 5% occurrence of green level damage, and the capacity reduction is equally distributed from 0-20%.

This distribution functions amplifies the bending moment.

9.4.7 Uncertainty tolerance

Uncertainties are for example related to the use of FEM-models, analytic models etcetera. Therefore, an additional effect (UT) is added. This is done conform EN1990 article 6.3.2. The uncertainty tolerance distribution is a normal distribution with a mean of $\mu = 1$ and a standard deviation of $\sigma = 0.05$. This is conform [2].

9.5 Monte Carlo analysis

9.5.1 General

For all the cases of Table 4 and Table 5 the load effect E_i value is calculated. This is done 100,000 times. Combining the load effects according to Table 15 leads to a distribution of the total load effect.

Table 15 - Beam bending equations

Pallets per beam	Combined load effect for beam
1	$E_i = 1/8 \cdot UT \cdot L \cdot \beta_{dynamic} \cdot F_{UDL,1} \cdot [1/2 \cdot UL_1 \cdot EP_{1,i} \cdot CG_{1,i}] \cdot GL_i$
2	$E_i = 2/8 \cdot UT \cdot L \cdot \beta_{dynamic} \cdot F_{UDL,2} \cdot [0.5 \cdot 1/2 \cdot UL_1 \cdot EP_{1,i} \cdot CG_{1,i} + 0.5 \cdot 1/2 \cdot UL_2 \cdot EP_{2,i} \cdot CG_{2,i}] \cdot GL_i$
3	$E_i = 3/8 \cdot UT \cdot L \cdot \beta_{dynamic} \cdot F_{UDL,3} \cdot [0.26 \cdot 1/2 \cdot UL_1 \cdot EP_{1,i} \cdot CG_{1,i} + 0.48 \cdot 1/2 \cdot UL_2 \cdot EP_{2,i} \cdot CG_{2,i} + 0.26 \cdot 1/2 \cdot UL_3 \cdot EP_{3,i} \cdot CG_{3,i}] \cdot GL_i$

E_i	Load effect from repetition no. i
L	Beam length
$F_{UDL,j}$	Correction factor for UDL instead of Concentrated loads
UL	Variable unit load (Yearly extreme distribution)
EP	Variable effect of eccentric pallet position (Equal distribution)
CG	Variable effect of shifted center of gravity (Normal distribution)
$\beta_{dynamic}$	Dynamic factor for vertical placement
GL	Effect of Green level; amplifies the bending
UT	Uncertainty tolerance to compensate for uncertain assumptions

An example with all distributions plotted as histogram can be seen in Figure 7.

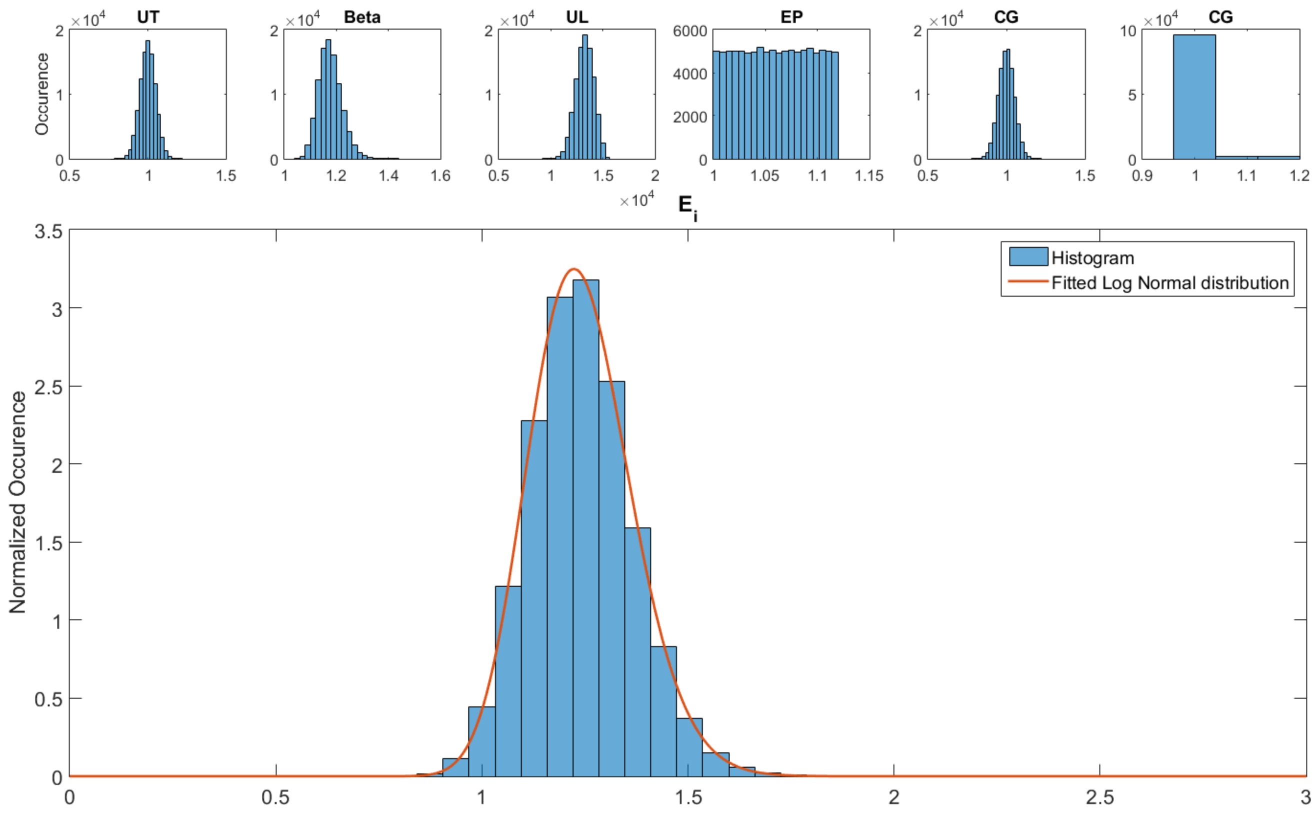


Figure 7 - Example calculation for case 1

9.5.2 Results of Monte Carlo

A maximum like hood estimation fit is performed to the distributions of the total load effect E. This is done for a total of 17 distributions fits (see Table 16). The results of this fit for all 36 can be found in Figure 8 and Figure 9.

For simplicity, one distribution is chosen to be fitted on all load effect distributions E. In EN1990 only three distributions are discussed, therefore the best fitting MLE distribution of these three (Normal, Log-normal and Gumbel) is chosen. For the Beam Monte Carlo analysis this is a Log-Normal distribution (for 34 of the 36 distributions this gives the best fit).

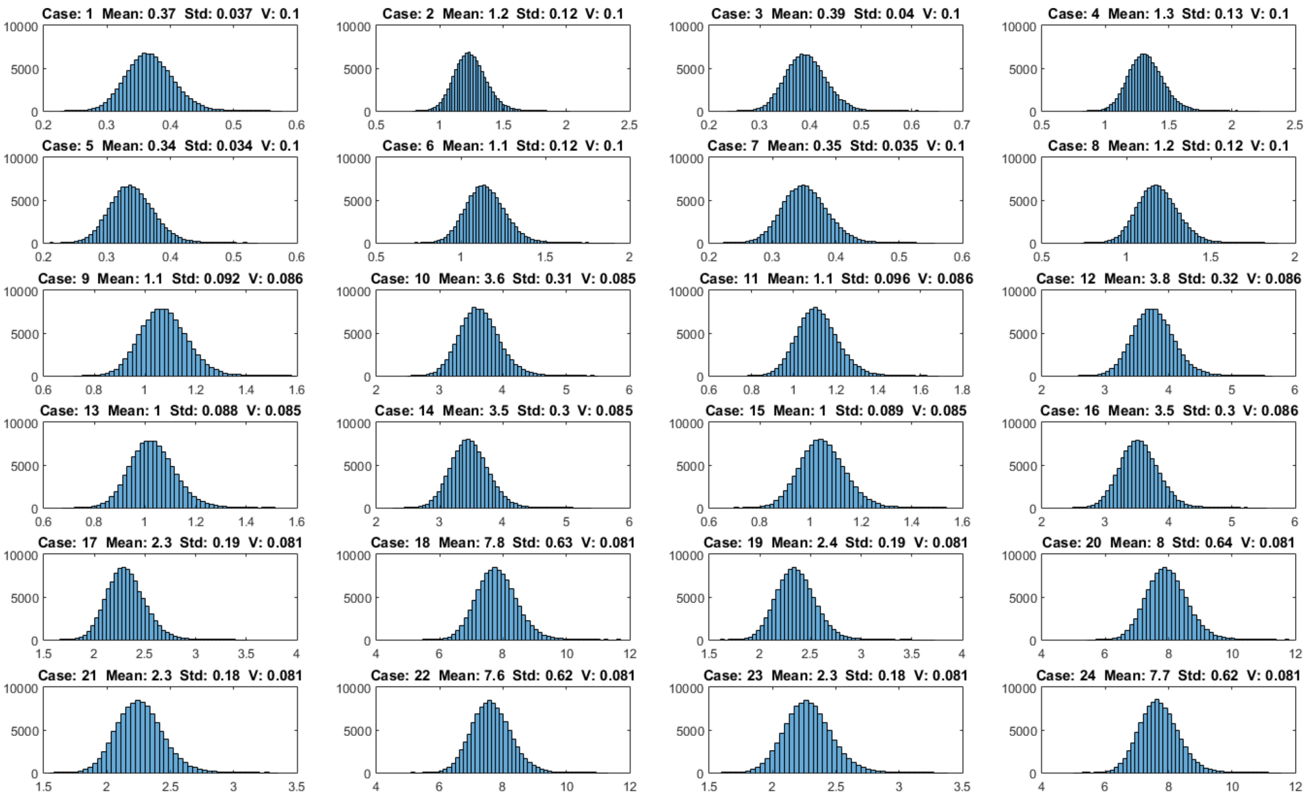


Figure 8 - Results of the first 24 cases and their best fit

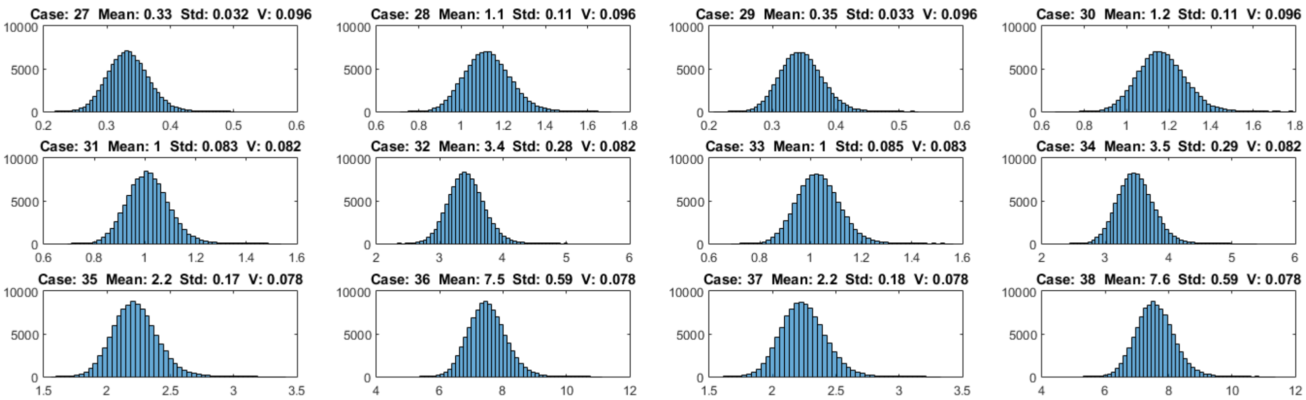


Figure 9 - Results of the weight checked 12 cases and their best fit

Table 16 - Distributions fitted to results

Distributions fitted to results		
Beta	Generalized Pareto	Normal
Birnbaum-Saunders	Inverse Gaussian	Rayleigh
Exponential	Logistic	Rician
Extreme value	Log-logistic	t location-scale
Gamma	Lognormal	Weibull
Generalized extreme value	Nakagami	

9.6 Design procedure

9.6.1 According to EN 15512:2009

For the beam the following effects are considered

- Pallet load (Unit load) UL
- Vertical placement load V_{pl}
  - 1 UL per compartment $V_{pl} = 0.25$ UL
  - 2 or more UL's per compartment $V_{pl} = 0.0$ UL

The maximal value of the following combination is considered;

$$ULs = maximum(0.9 \cdot \gamma_l \cdot \gamma_c \cdot (UL + V_{pl}) \quad , \quad \gamma_l \cdot \gamma_c \cdot (UL)) \tag{5}$$

- $M_{k,i} = \gamma_l \cdot \gamma_c \cdot Q_{load} \cdot 0.9 \cdot (1 + V_{pl}) \cdot \frac{1}{8} \cdot L^2 \cdot F_{UDL,i}$
- $M_{k,i} = \gamma_l \cdot \gamma_c \cdot Q_{load} \cdot \frac{1}{8} \cdot L^2 \cdot F_{UDL,i}$

γ_l depends on the type of operation

- For MAN/AUT, $\gamma_l = 1.4$
- For AUT with Weight check, $\gamma_l = 1.3$

9.6.2 Required amendments

9.6.2.1 Vertical placement load

This following is implemented in the prEN 15512:2018 for one UL per compartment:

- automatically operated systems
  - $V_{pl} = 0.30$ UL (was 0.25 UL in EN 15512:2009)
- manually operated systems
  - $V_{pl} = 0.70$ UL (was 0.25 UL in EN 15512:2009)

9.6.2.2 Modelling of pallet load

In case of 1 UL per compartment the load of the pallet cannot be represented by a UDL, since this leads to an underestimation of the bending moment of 26% (see Table 13). Therefor the pallet load shall be modelled with concentrated loads at the appropriate locations (see Figure 10). This is implemented in the prEN 15512:2018.

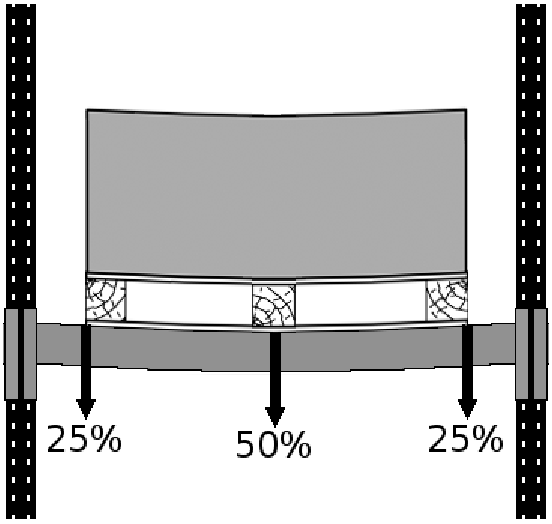


Figure 10 - Showing disposition of loads

9.7 Calculation of the correction factor

In this section, the correction factor is calculated to meet the target reliability.

The distributions of E_i for all 36 cases are shown in Figure 14 and Figure 15. In combination with the calculated design loads of 9.6 a suitable γ_{cor} can be found. This is done using equation 24 of Table C3 from EN 1990. The value for α = -0.7 and the value for β = 4.7. The choice of α = -0.7 is correct since 0.76 > σ_E / σ_R > 0.16 see Annex C.

$$\gamma_{cor} = \frac{\mu_i \cdot exp(-\alpha \cdot \beta \cdot V_i)}{Q_{k,i}} \qquad for \qquad V_i = \frac{\sigma_i}{\mu_i} < 0.2 \qquad (6)$$

9.7.1 Corrected dynamic effect for single pallet compartments

Figure 11 shows an average correction factor γ_{cor} of 1.1. With the corrected dynamic effect for a single pallet compartment, case 3 and 4 show a relative high correction factor; approx. 1.27. This is 15% more than the average γ_{cor} of 1.1.

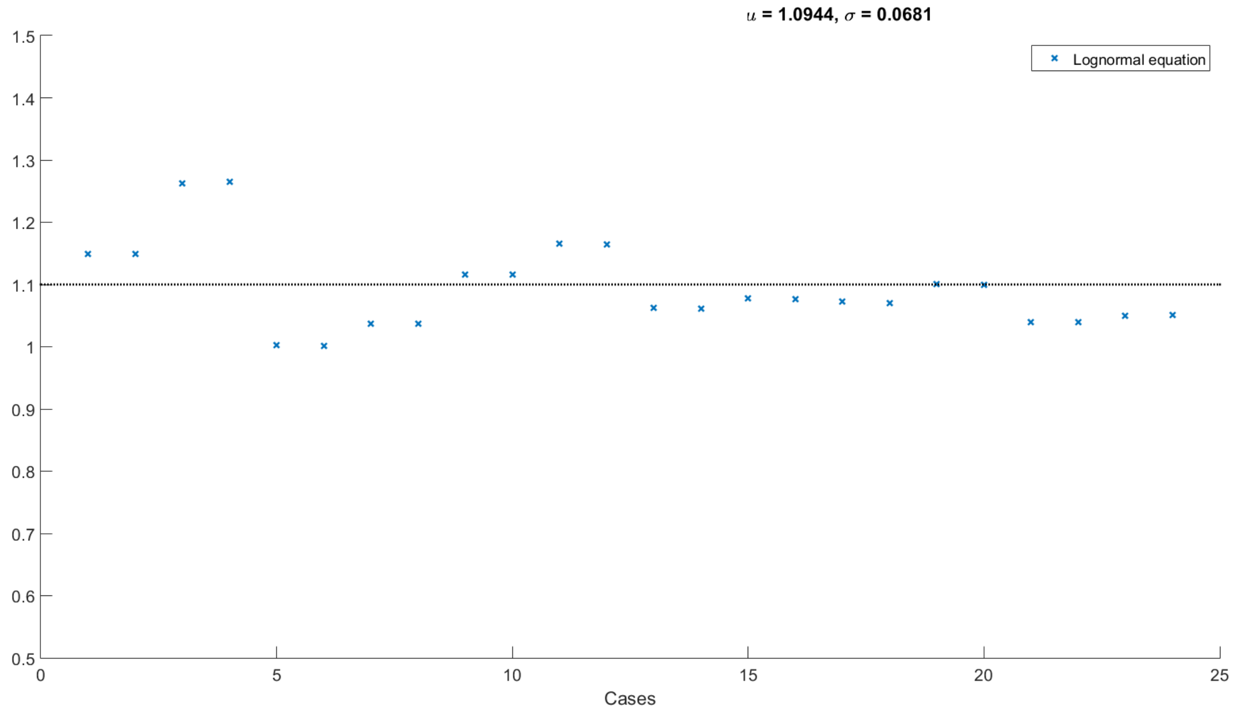


Figure 11 - Results of the first 24 cases for RC2 (no weight check)

Several factors contribute to this exceedance of case 3 and 4. The In the next section, the effect of the statistical distribution for the vertical placement speed is examined.

9.7.2 Adjustment of statistical distribution for the vertical placement speed for RC2

As explained in 0 case 3 and 4 show a relatively high correction factor. An important parameter is the statistical distribution of the vertical placement speed. As shown in Table 12, the average placement speed is 0.15 m/s for manually operated racking systems. The original statistical distribution is plotted in Figure 12 – Distribution Figure 12. The green line represents the speed distribution for automated racking and the red line for manually operated racking.

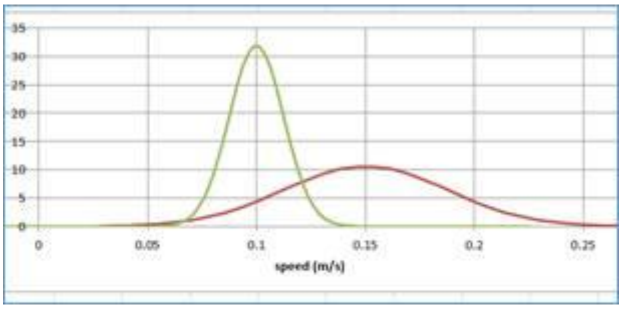


Figure 12 – Distribution μ=1/4 for manual operated (red line) and μ=1/8 for automatic operated (green line)

This relatively wide distribution leads to a large scatter in the Monte Carlo results and therefore a larger correction factor. The effect of a less wide distribution (see Figure 13) is investigated.

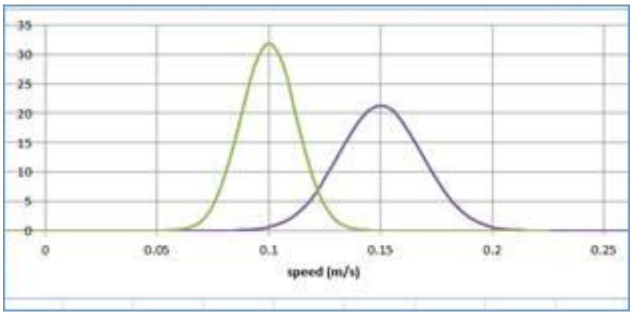


Figure 13 – Distribution μ=1/8

Since the mean value of 0.15 m/s is conservative and the distribution covers speeds between 0.075 and 0.225 m/s, the normal distribution with μ=1/8 seems acceptable.

The rerun of the Monte Carlo analysis leads to acceptable results (see Figure 14). The correction factors for case 3 and 4 have dropped to 1.158. This is only a 5% exceedance of γ_{cor} = 1.1.

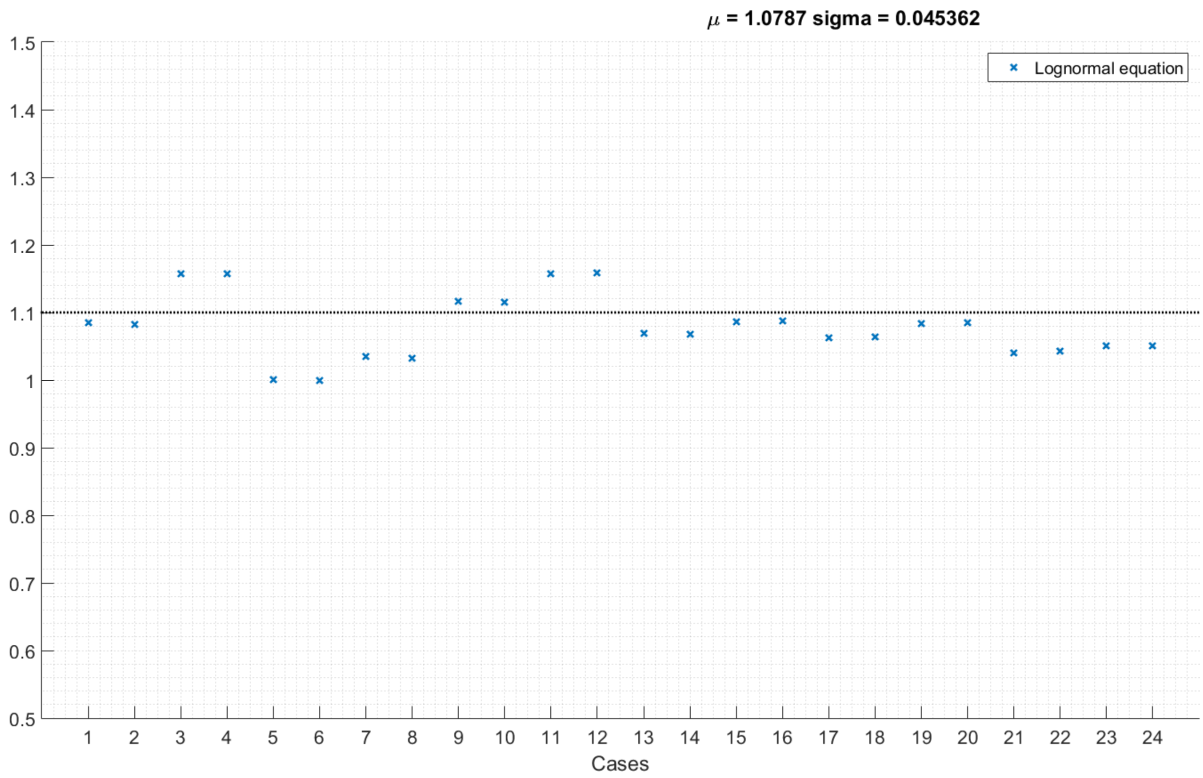


Figure 14 - Results of the first 24 cases for RC2 (no weight check)

Figure 14 and Figure 15 show the results of all 36 cases. The mean value factors is 1.08.

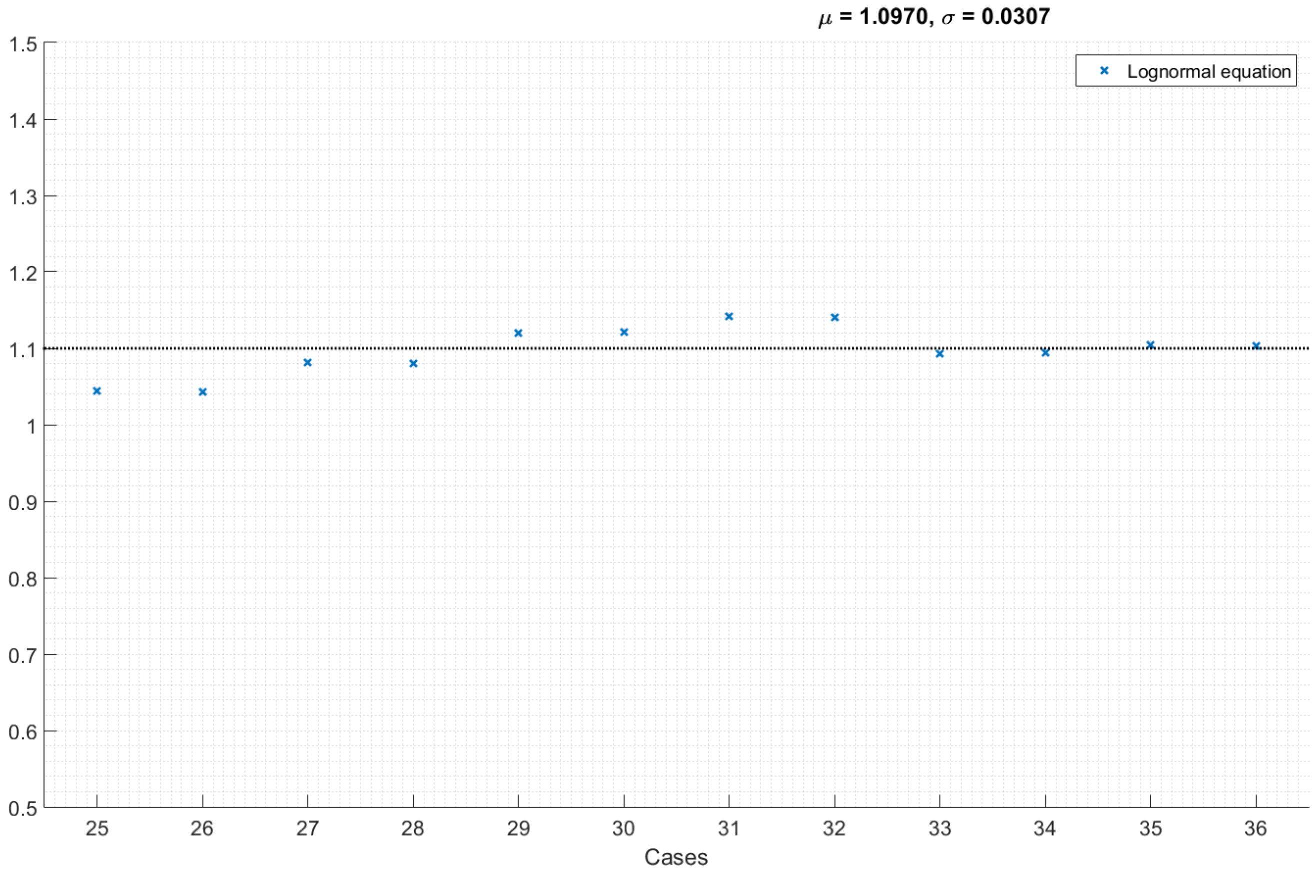


Figure 15 - Results of the last 12 cases (weight check and refusal)

9.7.3 Adjustment of statistical distribution for the vertical placement speed for RC1

The rerun of the Monte Carlo analysis with β=4.2 (RC1) leads to the following results (see Figure 16).

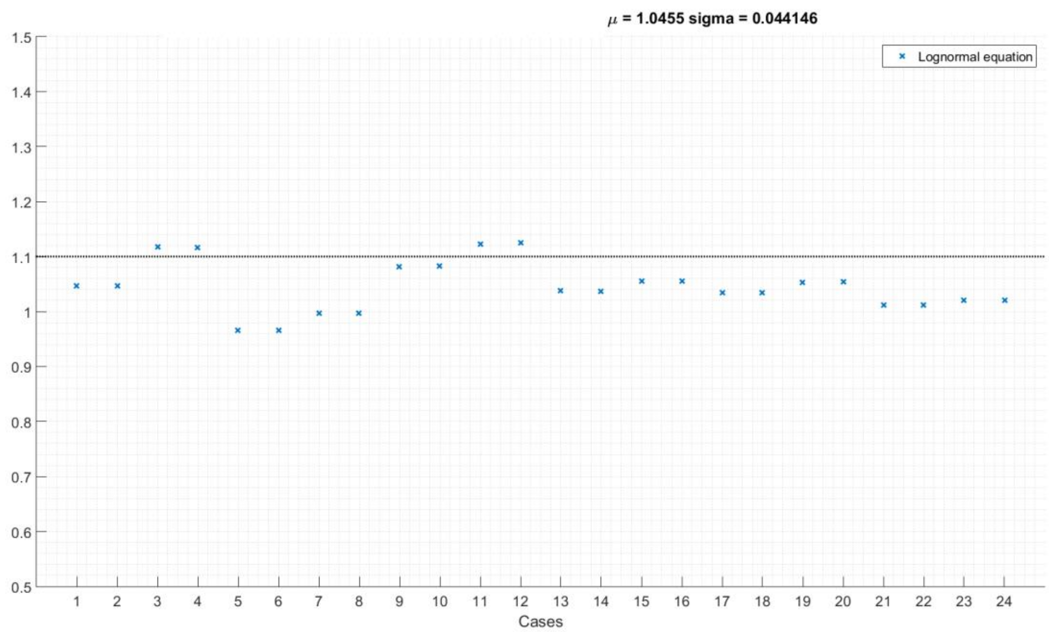


Figure 16 - Results of the first 24 cases for RC1 (no weight check)

Figure 16 and Figure 17 show the results of all 36 cases for RC1.

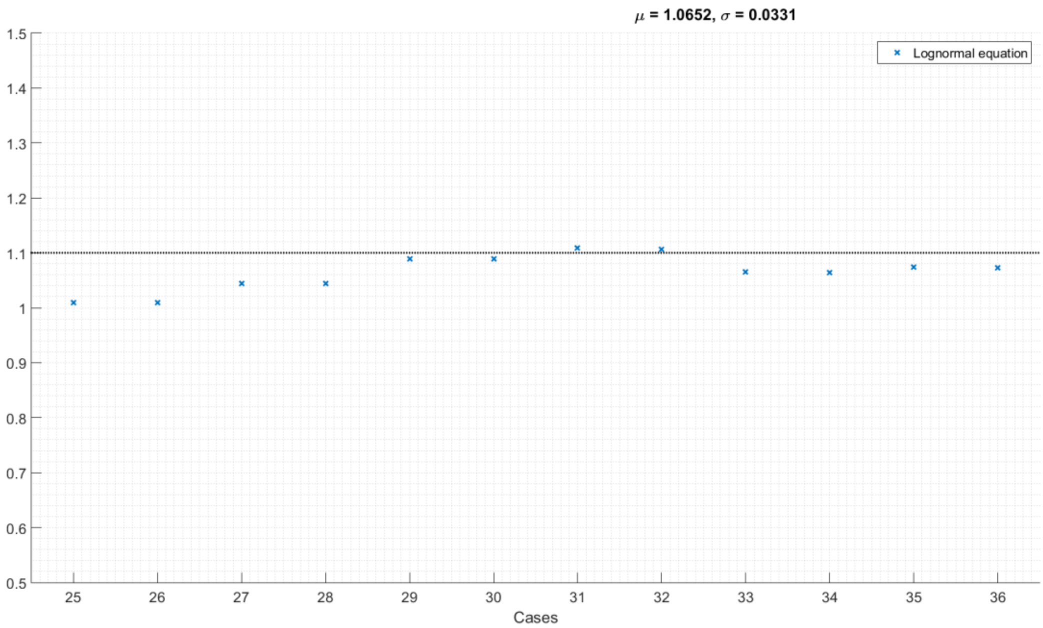


Figure 17 - Results of the last 12 cases for RC1 (weight check and refusal)

9.7.4 Adjustment of statistical distribution for the vertical placement speed for RC3

The rerun of the Monte Carlo analysis with β=5.2 (RC3) leads to the following results (see Figure 16).

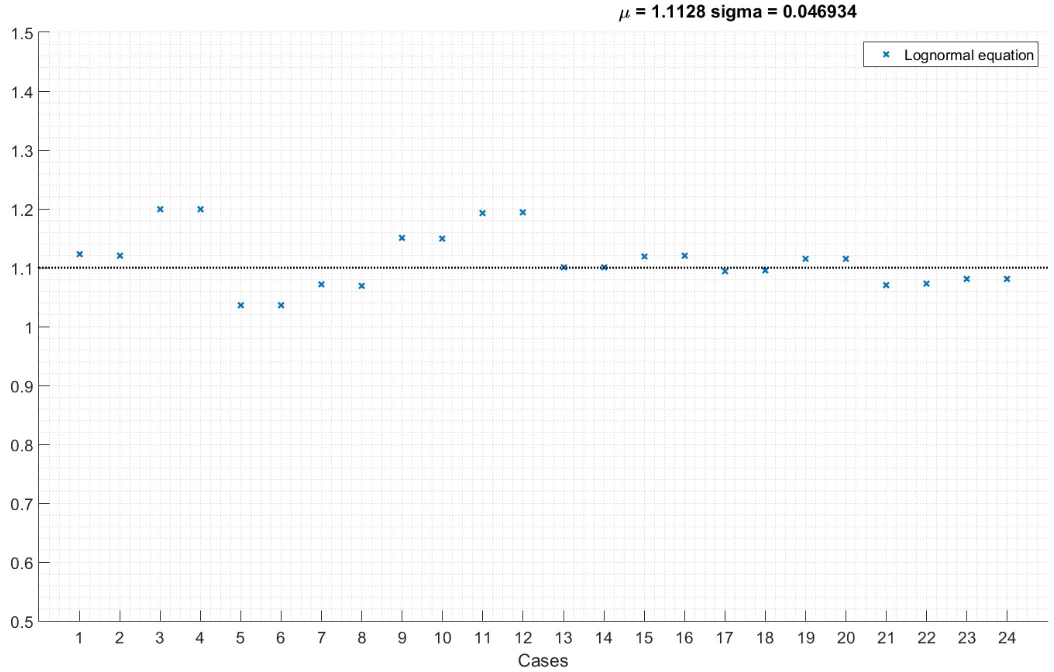


Figure 18 - Results of the first 24 cases for RC3 (no weight check)

Figure 16 and Figure 17 show the results of all 36 cases for RC3.

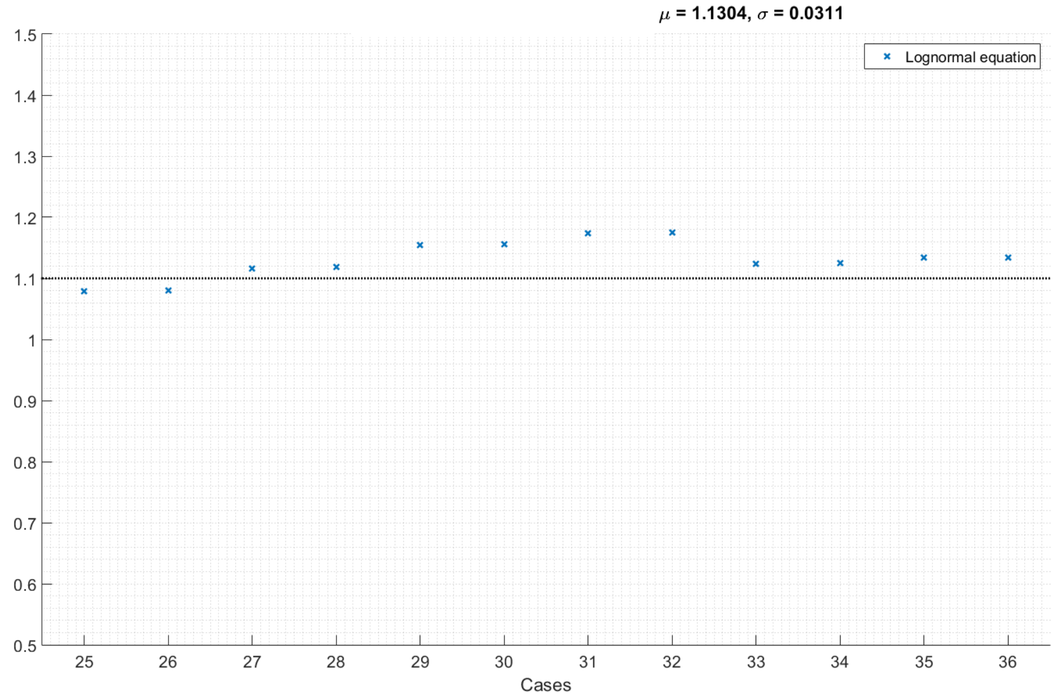


Figure 19 - Results of the last 12 cases for RC3 (weight check and refusal)

9.7.5 Exceptional case for RC2

Figure 14 and Figure 15 show some cases with a higher value than 1.1. Only the cases with an exceedance of 5% ($\gamma_{cor} \geq 1.155$) are listed. The highest values are noted in Table 17. Cases 3, 4, 11 and 12 show a higher correction factor, but still close to this 5% and do not need further explanation. (At this point, it must be mentioned that for traditional structures, in several cases safety factors are obtained from reliability analyses that are significantly higher than the factors finally defined in the Eurocodes, see for example [4] and [5]. In these examples the exceedance is often much higher than 5 %.)

Table 17 - Exceptional cases

		pallets per compartment	Qp	L	stiffness requirement	Operation	Value
Problem	Case	n	(kN)	(mm)	L/		
No Weight check	3	1	4	950	300	MAN	1.158
No Weight check	4	1	13.5	950	300	MAN	1.158
No Weight check	11	2	4	1825	300	MAN	1.158
No Weight check	12	2	13.5	1825	300	MAN	1.158

9.7.6 Conclusion RC2

The mean value of γ_{cor} 1.09. Therefore, γ_{cor} =1.10 is proposed.

10 Reliability design Frames

10.1 Introduction

In EN 15620 the floor slab is defined as quasi rigid when the slab rotation due to the applied rack load is less than 1/2000 (0.5 mrad). In case of a quasi-rigid slab, the effects of slab deformation need not be considered.

It is common practise to design a pallet rack assuming a quasi-rigid slab. However, it is unrealistic that this requirement is met for most of the realised structures especially for the manually operated pallet racking. On the other hand the industry is not confronted with problems due to excessive local slab rotations.

A table with realistic floor slab rotations is implemented in the prEN 15512:2018 (see Table 18). The rotation (deformation) of the floor slab influences the internal forces in the racking system, and therefore the actual safety level of the system (see Figure 20). In this report a probabilistic approach was used to verify the reliability.

The limiting rotation Φ_{floor} is 50% of the specified installation accuracy.

Table 18 - Floor deformation limits for quasi-rigid assumption (prEN 15512:2018)

Specified Installation Out-of-plumb	Limiting rotation ϕ_{Floor} in serviceability limit state (see Figure 20)
1 / 350	1 / 700
1 / 500	1 / 1000
1 / 750	1 /1500
1 / 1000	1 / 2000

The analysis shows that with some small modifications the slab rotation can be included in the safety philosophy in case the frames are bolted together. Bolted frames have a frames shear stiffness between

300 and 2000 kN/rad and the looseness in the bolted connections also helps to relax the influence of the slab.

For welded frames the frame shear stiffness is higher (2000 up to 8000 kN/rad) and there is no looseness leading to significant additional internal forces. Therefore, it is recommended for welded frames to consider the effects of the floor slab rotations in a load case instead of including the rotation of the slab effect in the partial factors.

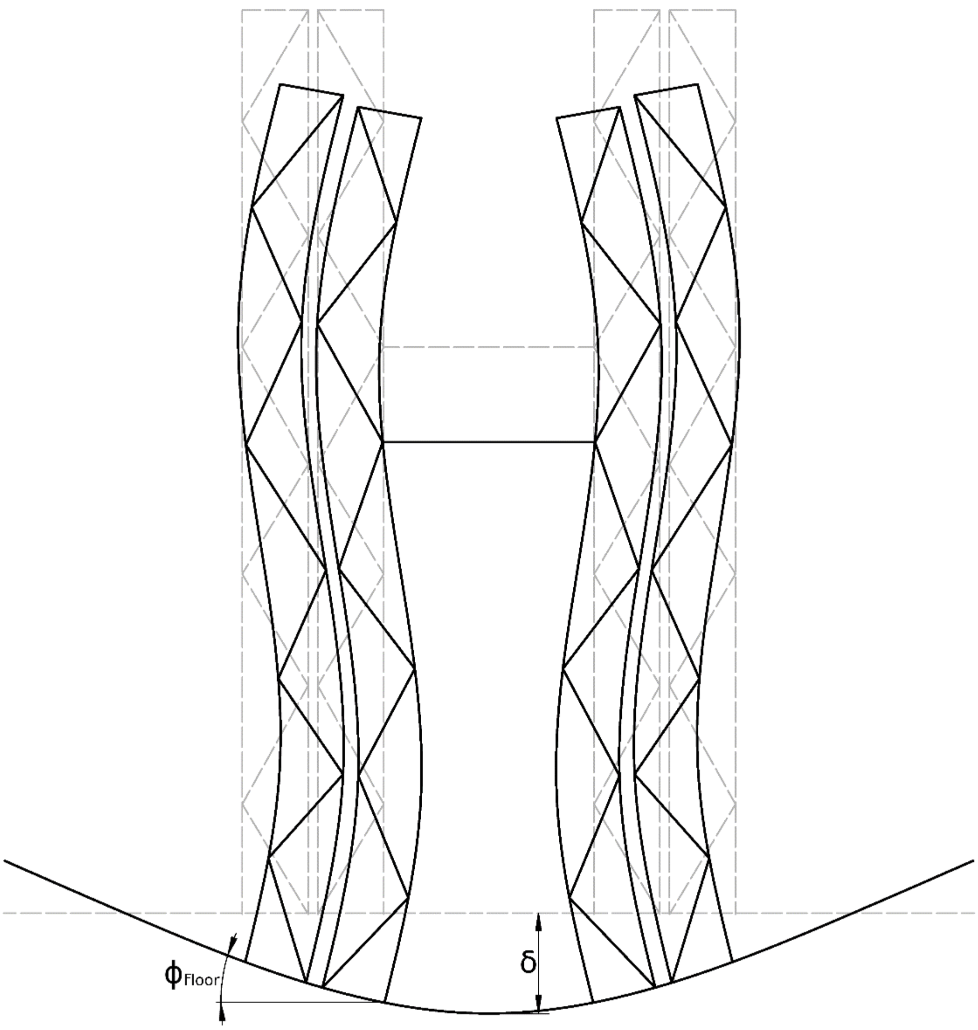


Figure 20 - Example of the inter-relationship between floor slab and rack deflection

Key

ϕ_{Floor}	slab rotation
δ	slab deflection

10.2 Reliability class

See 9.2.

10.3 Cases

In order to get a reliable recommendation, sufficient cases need to be considered. The biggest structural difference between automated and manual operated APR is that the automated APR is connected at the top in cross-aisle direction whereas manual operated APR is generally not (see Figure 41). In total 34 cases are defined to reflect the scope of EN 15512. The welded frames do not include cases with a weight check and refusal system, since the first cases for welded frames showed that the effects of the floor slab cannot be included.

- Three handling principles of load units.

a) Manual operated warehouses

- 16 cases
- Unit load (pallet) weights (4 kN / 13.5 kN)
- Single frames and double frames
- Height smaller than 20 meter (VNA trucks)
- 3 to 10 levels
- Installation imperfection 1/350, 1/500 and 1/750
- Slab rotations 1/700, 1/1000 and 1/1500

b) Automatic operated warehouses - no check of unit load weight

- 12 cases
- Unit load (pallet) weights (4 kN / 13.5 kN)
- Frames are connected in the top (at least 2 up to 40 frames)
- Height up to 30 meter
- 5 to 15 levels
- Installation imperfection 1/1000
- Slab rotations 1/2000

c) Automatic operated warehouses - check of unit load weight and refusal

- 6 cases
- Unit load (pallet) weights (4 kN / 13.5 kN)
- Frames are connected in the top (at least 2 up to 40 frames)
- Height up to 30 meter
- 5 to 15 levels

    - Installation imperfection 1/1000
    - Slab rotations 1/2000

- Two types of adjustable pallet racking frames

  a) Bolted frames (90 % of frames in the market)

    - Due to non-pre-stressed bolted connections the frame has looseness
    - The frame shear stiffness is between 300 and 2000 kN/rad

  b) Welded frames (10 % of frames in the market)

    - Due to welded connections the frame has no looseness
    - The frame shear stiffness is between 2000 and 8000 kN/rad

  Because of the large difference in frame shear stiffness both types are considered.

Table 19 - Overview of bolted frame cases

		Case	Q_p (kN)	Inst. Imp 1/	Φ_F 1/	H (m)	levels	Operation
bolted frames APR	Manually operated	1	4	350	700	6	3	MAN
		2	13.5	350	700	6	3	MAN
		3	4	350	700	10	5	MAN
		4	13.5	350	700	10	5	MAN
		5	4	500	1000	10	5	MAN
		6	13.5	500	1000	10	5	MAN
		7	4	750	1500	20	10	MAN
		8	13.5	750	1500	20	10	MAN
	Automatically operated no weight check	9	4	1000	2000	10	5	AUT
		10	13.5	1000	2000	10	5	AUT
		11	4	1000	2000	20	10	AUT
		12	13.5	1000	2000	20	10	AUT
		13	4	1000	2000	30	15	AUT
		14	13.5	1000	2000	30	15	AUT
	Automatically operated - weight check	15	4	1000	2000	10	5	AUT - W
		16	13.5	1000	2000	10	5	AUT - W
		17	4	1000	2000	20	10	AUT - W
		18	13.5	1000	2000	20	10	AUT - W
		19	4	1000	2000	30	15	AUT - W
		20	13.5	1000	2000	30	15	AUT - W

Table 20 - Overview of welded frame cases

		Case	Q_p (kN)	Inst. Imp 1/	Φ_F 1/	H (m)	levels	Operation
welded frames APR	Manually operated	21	4	350	700	6	3	MAN
		22	13.5	350	700	6	3	MAN
		23	4	350	700	10	5	MAN
		24	13.5	350	700	10	5	MAN
		25	4	500	1000	10	5	MAN
		26	13.5	500	1000	10	5	MAN
		27	4	750	1500	20	10	MAN
		28	13.5	750	1500	20	10	MAN
	Automatically operated no weight check	29	4	1000	2000	10	5	AUT
		30	13.5	1000	2000	10	5	AUT
		31	4	1000	2000	20	10	AUT
		32	13.5	1000	2000	20	10	AUT
		33	4	1000	2000	30	15	AUT
		34	13.5	1000	2000	30	15	AUT

10.4 Load effects

The identified load effects that have been taken into account in the Monte Carlo analysis, are discussed in this section.

10.4.1 Unit load

The influence factor per UL for the middle upright is taken into account. The influence of each pallet can be seen in Figure 21.

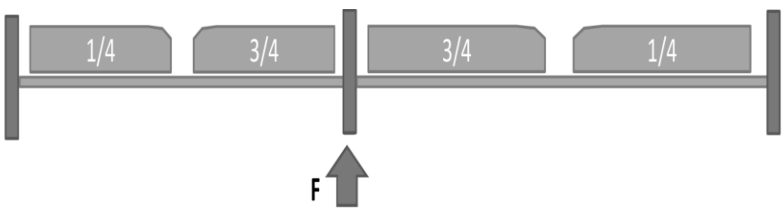


Figure 21 - Influence of each pallet for two pallets per compartment

Furthermore, the pallet loads from section 4.1 are again used in the frame analysis.

10.4.2 Unit load placement eccentricity and center of gravity eccentricity

The effect of load placing eccentricity is different for frames then it is for beams. Since the frame is loaded with at least 12 beams ((3 beams left and right) multiplied by (front and rear)), it therefore is assumed that these eccentricity effect are neutralized and thus will not be considered into the frame analysis.

10.4.3 Vertical placement load

The vertical direction in pallet racking is the axis parallel to the uprights, and the horizontal direction is the direction orthogonal to the beams and orthogonal to the uprights. In both horizontal and vertical directions there will be a load when placing a pallet.

Due to the vertical placing load there will be a dynamic effect in which the static load deformation will be exceeded. Once again it is assumed that all unit loads have the same weight. A conservative value of $\beta_{dynamic}$ =1.3 is chosen. As it is expected that with a high number of levels the dynamic placing effect will be not much of an influence. This effect can be seen in Table 21.

Table 21 - Dynamic effect per height number of levels

2 cheps per compartment			
3	Levels	Effect:	1.04
5	Levels	Effect:	1.02
10	Levels	Effect:	1.01
15	Levels	Effect:	1.01

10.4.4 Horizontal placement load

Rules for following the horizontal placement load can be found in the EN 15512:2009. A summary can be found in Table 22.

Table 22 - Rules for calculating the horizontal placement load

Height:	≤3m	Horizontal load:	0.5	kN
Height:	3m < h < 6m	Horizontal load:	$0.75 - {}^{1}/_{12}\,h$	kN
Height:	≥6m	Horizontal load:	0.25	kN

10.4.5 Crane load

For the cases of automatic operation, two cases are investigated. Single and double deep storage: an overview can be seen in Figure 22.

Lateral reaction force in top:

- Single deep storage
  - $H_{cr} = (Q_{UL} + SW_{SD})\frac{e}{h}$
    with $e = 1.5m$

- Double deep storage
  - $H_{cr} = (Q_{UL} + SW_{SD})(\frac{1}{2}\,W_{aisle} + \frac{3}{2}\,W_{UL})/h$
    with $e = 3m$

H	Lateral support force in top of rack
h	Height rack
Q_{UL}	Weight unit load
SW_{SD}	Self-weight forks for single deep
SW_{DD}	Self-weight forks for double deep
e	Length of the fork

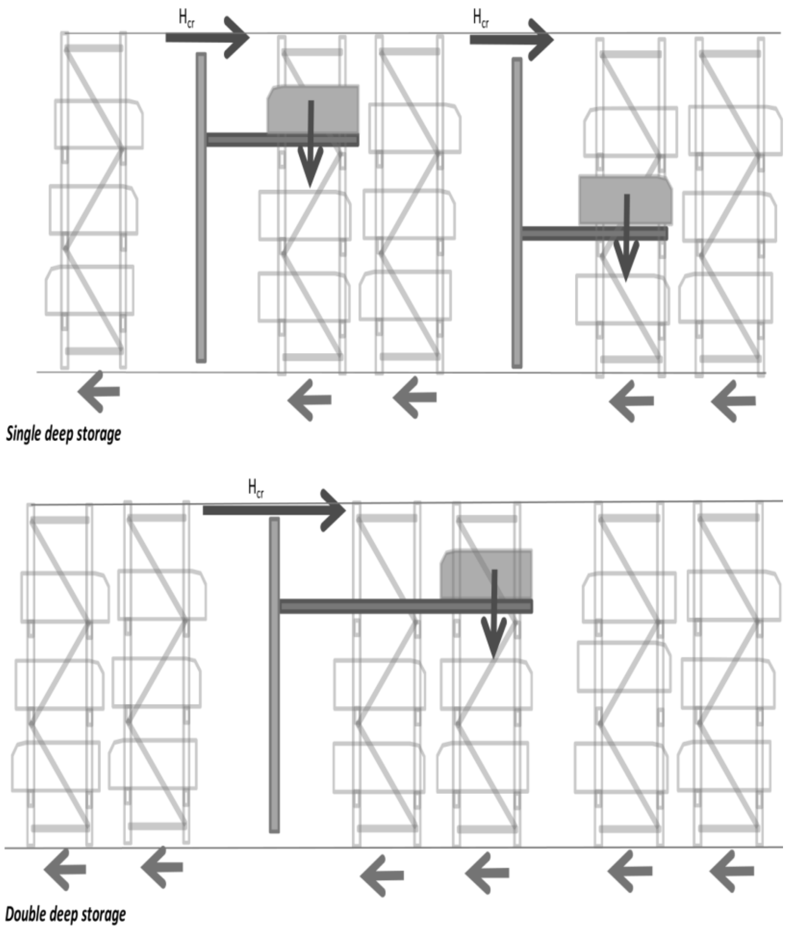


Figure 22 - Overview of single and double deep storage

The lateral support force of the double deep situation is approximately 2 times as high as the single deep situation. Since the double deep situation has twice the number of frames, the two situations are assumed to be more or less identical. Therefore, only the single deep situation is considered.

10.4.6 Frame looseness

Frame looseness relaxes the stress in the frames, caused by deformation of the slab. On the other hand the looseness also causes that not all frames are activated at the same time. Both effects are considered.

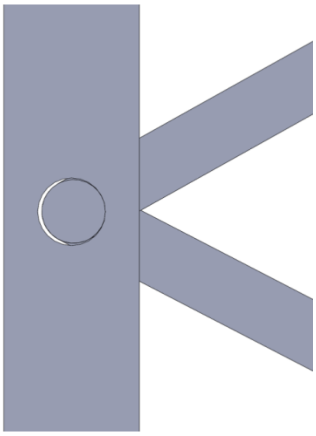
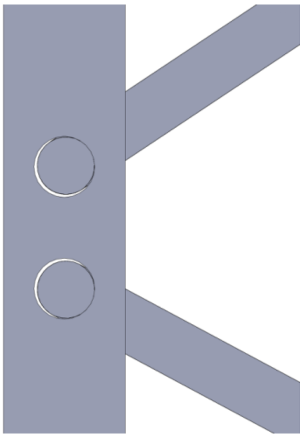
$$\phi_{L\ one\ point} = \frac{2\,s_u}{d} + \frac{2\,s_d\,\sin(\alpha)\,\left(\frac{1}{\tan(\alpha)^2}+1\right)}{d} = \frac{2\,s_d + 2\,s_u\,\sin(\alpha)}{d\,\sin(\alpha)} \quad (7)$$

$$\phi_{L\ two\ points} = \frac{\sin(\alpha)\,(2\,s_d + 2\,s_u)\,\left(\frac{1}{\tan(\alpha)^2}+1\right)}{d} = \frac{2\,s_d + 2\,s_u}{d\,\sin(\alpha)} \quad (8)$$

d	frame depth crs
dfas	diameter fastener
dup	diameter upright
ddia	diameter diagonal
su	looseness upright
sd	looseness diagonal
	average diagonal angle

Equations 7 and 8 are taken from prEN15512:2018.

Table 23 - Two different forms of diagonal connection

Diagonals at one point, see equation 7	Diagonals at two point, see equation 8
	

Theoretically the looseness angle is equal to both sides. In practice (after installation) this will not be the case. For the installation angle in relation to the theoretical central two uniform distribution are assumed.

The looseness (ϕ_L) is set in one direction and is set to 1 mrad. Resulting in a uniform distribution ranging from -1 mrad to 1 mrad. (see Figure 23) This will result in a total looseness of 2 mrad.

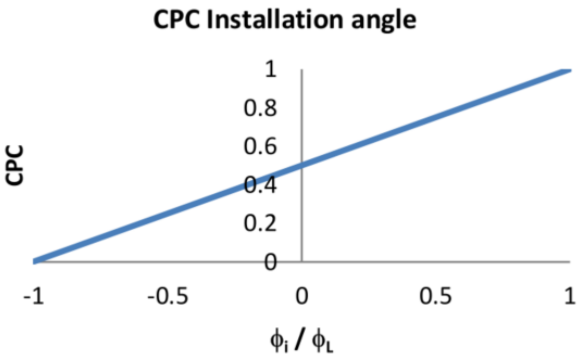
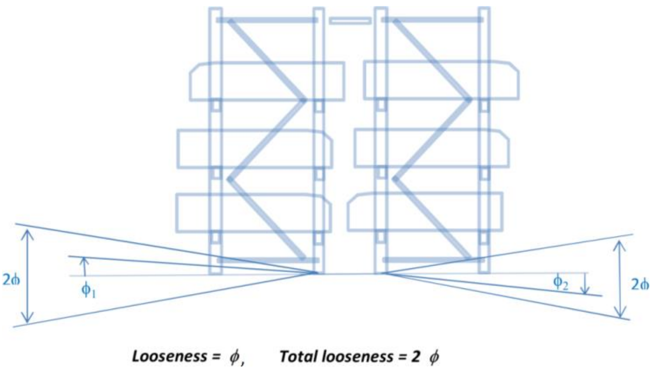
CDF of looseness distribution	Explanation of total looseness
	

Figure 23 – Looseness distribution

10.4.6.1 The effect on lateral loads (for bolted frames)

General formulation of lateral load per frame:

$$R_i = S_d^* \cdot (\frac{\delta}{h} - \Delta\Phi_i) \geq 0 \qquad (9)$$

$$\Delta\Phi_i = \Phi_L - \Phi_I - \Phi_F(-1)^i \qquad (10)$$

$$H = \Sigma R_i \qquad (11)$$

h	frame height
δ	lateral sway
H	lateral load
R_i	lateral reaction force for frame i
Φ_L	looseness (± 1 mrad)
Φ_i	uniform distribution ⍰L to ⍰L
Φ_F	slab rotation

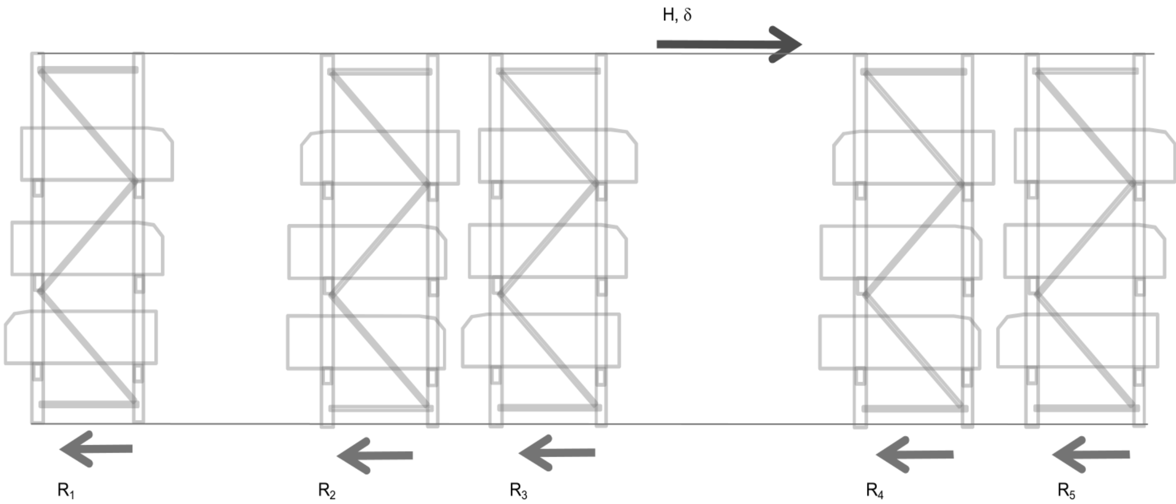


Figure 24 – Overview of terms used in equations 9

Due to all effects (looseness, slab rotation and installation) not all frame will be loaded equally. This leads to an amplification factor (some frames are more loaded than others)

$$\Omega = \frac{\max(R_i)}{\text{average}(R)} \tag{12}$$

10.4.6.1.1 Manually operated racking

The slab rotation leads to shear forces in both frames ($R_1 = -R_2$). When the lateral load H (imperfection and horizontal placement load of both frames) is smaller than R_1 , H is divided over both frames, otherwise H is taken by one frame only.

In general: When the influence of the slab is high, the amplification factor will be 1, otherwise 2.

10.4.6.1.2 Automatically operated racking

The slab rotation is relative low (0.5 mrad) compared to the looseness (1 mrad). This means that additional lateral loads may be irregular divided over all frames.

Automatically operated APR laterally supports handling equipment. This leads to significant higher lateral loads compared to manually operated APR. These lateral loads vary between approx. 0.1 and 2 kN per frame.

For higher lateral loads the effects like looseness and slab rotation become less important and the amplification factor goes in the direction of 1. For small lateral loads the effects are important and the amplification factor is relatively high (2 up to 2.5).

The amplification factor is determined for all defined automatically operated APR cases.

For simplification the amplification factors are determined in this section, because the iterative calculation is difficult to combine with Monte Carlo. The obtained parameters are used as input for the analysis (normal distribution).

10.4.6.1.3 Conclusion

The lateral loads (placement load, imperfection loads and crane loads) are not equally distributed over the number of connected frames. To show this effect the amplification factor is plotted as function of the lateral load for case 9 (see Figure 27). This shows that for small lateral loads the amplification is relatively large and for large lateral loads the amplification factor becomes relatively small. The mean values of the amplification factor for case 9 till 20 vary between 1.6 to 1.8 see Table 24.

	Ω	
H (N)	**μ**	**σ**
250	2.48	0.368
500	1.85	0.195
750	1.57	0.105
1000	1.44	0.077
1250	1.34	0.063
1500	1.30	0.054
1750	1.25	0.045
2000	1.22	0.041

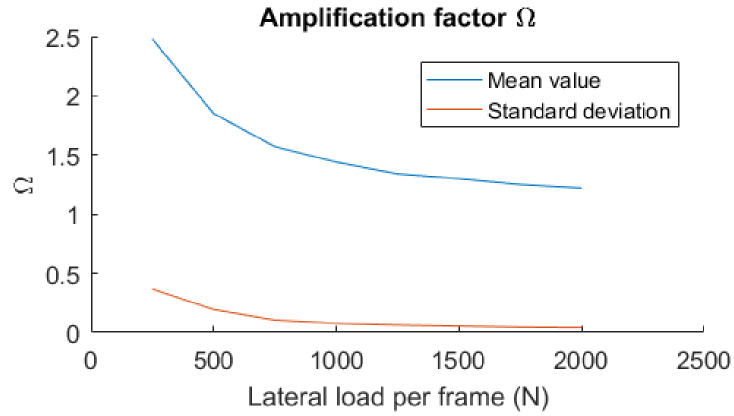


Figure 25 – Graph of Amplification factor vs. Lateral Load for case 9

Table 24 - Amplification factors for relevant cases

Bolted frames													
Case		9	10	11	12	13	14	15	16	17	18	19	20
amplification Factor Ω	**μ**	1.8	1.6	1.8	1.7	1.7	1.6	1.8	1.6	1.8	1.7	1.7	1.6
	σ	0.18	0.11	0.16	0.14	0.15	0.10	0.14	0.10	0.16	0.13	0.16	0.10

10.4.6.2 slab rotation in z-direction

According to Pieter Maas (Structural Engineer of Van Berlo industrial floor slabs) the 1/700 is too optimistic for "un-coordinated" design of slabs. In the Netherlands he believes one should design with 1/500 rotation. He stated that the theoretical design normally not includes:

- Uncertainty sub-soil; can be factor 1.5 off
- Chess board (pattern) loading; parts of slab heavily loaded and partly unloaded
- Edge effects

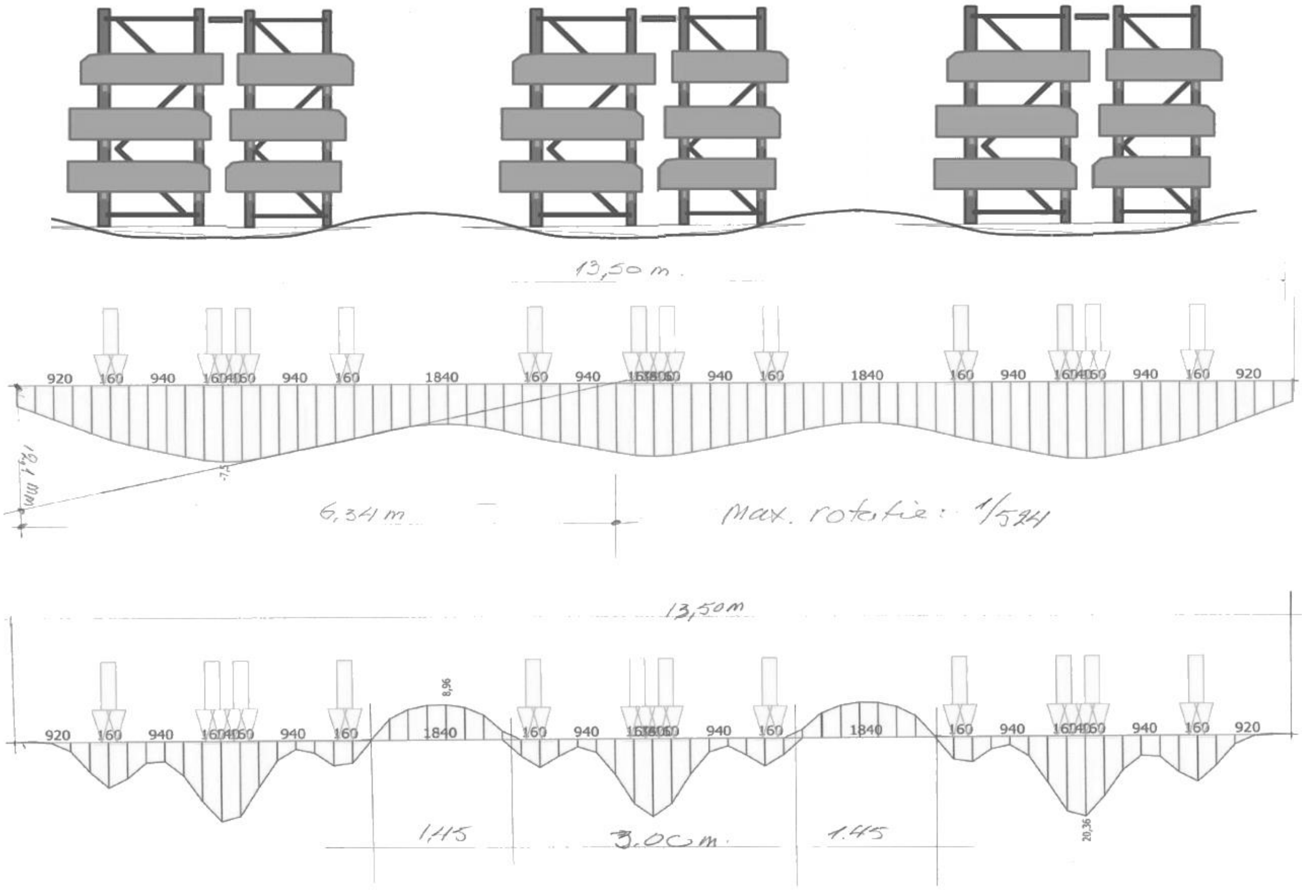


Figure 26 – Calculations by Pieter Maas

Table 25 - Amplification of slab rotation with a factor 1.25

Table taken from (FEM 10.2.14)		**Reliability design**
Specified installation out of plump	Allowable FF	FF* = 1.25 FF
1/350	1/700	1/600
1/500	1/1000	1/800
1/750	1/1500	1/1200
1/1000	1/2000	1/1600

Dr. Kraus contacted a German expert on this topic. This expert confirmed the 1/700 and sees Table 25 as realistic. It was decided to amplify the slab rotation (as defined in Table 25) with a factor 1.25, in order to be able to absorb some exceedance.

For simplification the two frames can be modelled with an opposite rotation at the base:

The residual effect of the slab rotation (including looseness) on the frame is (see equation 13):

$$\Phi_{res} = \Phi_F - \Phi_{L,slab} = \Phi_F - \left(\Phi_L - \frac{1}{2}(\Phi_1 - \Phi_2)\right) \quad (13)$$

Shear forces:

$$S = \Phi_{res} \cdot S_d^* \tag{14}$$

$$\Delta N_{up} = S \cdot \frac{h}{D_{crs}} \tag{15}$$

$$\Delta N_{up,max} = \Phi_{res} \cdot S_d^* \cdot \frac{h}{D_{crs}} \tag{16}$$

10.4.7 Very light racking

In case of very low concentrated loads the slab rotation as defined in Table 25 is too conservative. The following situation may be considered worse case (according to Pieter Maas):

- Upright load 75 kN
- Slab rotation 1/600

For Concentrated loads smaller than 75 kN the slab rotation may be reduced to, but not better than 1/2000;

$$\Phi_F = \frac{1}{600}(\frac{N}{75})^{\frac{1}{3}} \geq \frac{1}{2000} \tag{17}$$

10.4.8 Frame imperfections

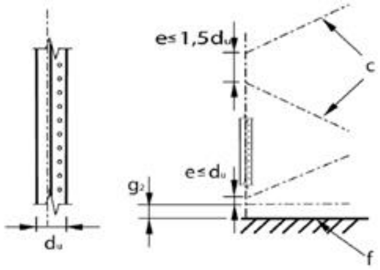
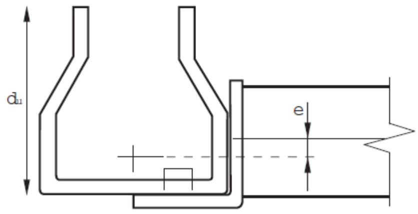
Installation imperfections are used in the Monte Carlo analysis. The installation imperfections used can be found in Table 19 and Table 20.

10.4.9 Eccentricities

10.4.9.1 General

When the criteria of clause 8.6 and 8.7 of EN 15512:2009 are fulfilled (see Table 26), these eccentricities may be ignored according to EN 15512:2009. The eccentricities are related to bending over the minor axis of the upright. Both criteria are geometrical criteria and not related to loads and/or stress contributions.

Table 26 - Section 8.6 and 8.7 from EN15512:2009

Section 8.6	Section 8.7
 **Key** c system lines d_u depth of upright e eccentricity between bracings f floor g_2 distance from floor to lower bracing node point **b) Eccentricities in frame bracing** **Figure 18 — Eccentricities**	**8.7 Eccentricities between beams and uprights** The centroidal axis of the beam may not coincide with the centroidal axis of the upright. This eccentricity 'e' in the cross-aisle direction as shown in Figure 12.  **Key** d_u depth of upright e eccentricity **Figure 12 — Eccentricity in the cross-aisle direction** The eccentricity e in Figure 12 may be neglected where 'e' is less than 0,25 d_u.

10.4.9.2 Frame bracing eccentricities

The influence of this eccentricity is studied in D.2. The conclusion is that the current criterion is sufficient in case the shear force in the frame is low. In case of high shear forces (wind, seismic and high crane loads) the stress contribution may be significant.

These eccentricities are not included in the study. Therefore, the contribution shall be limited. Considering the conservative nature of the representation of the two major load effects; unit load and slab rotation, a load effect of the eccentricities of 5% is acceptable. This shall be added to the standard.

10.4.9.3 Eccentricities between beams and uprights

The influence of this eccentricity is studied in D.3. The conclusion is that the current criterion is sufficient for normal cases. In case of a light upright with a high compartment load and high eccentricity the stress contribution may be significant.

These eccentricities are not included in the study. Therefor the contribution shall be limited. Considering the conservative nature of the representation of the two major load effects; unit load and slab rotation, a load effect of the eccentricities of 5% is acceptable. This shall be added to the standard.

10.4.10 Green level

According to EN 15635 a minor damage "Green Level" is allowed. Orange and red levels of damage need repair.

Damages classified as Green Level can lead to a capacity reduction of upright up to 20%. It is assumed that there is a 5% occurrence of green level damage, and the capacity reduction is equally distributed from 0-20%.

This distribution functions amplifies the upright load.

10.4.11 Frame shear stiffness

10.4.11.1Frame shear stiffness (S_d)

Table 27 - Frame shear stiffness of bolted frames

				Bolted Frames			
				Sd (kN/rad)		factiles	
Frame load (tons)		Nup		m	s (1/4 m)	5%	95%
	5		25	750	188	375	1125
5	10	25	50	1000	250	500	1500
10	20	50	100	1250	313	625	1875
20		100		1500	375	750	2250

Table 28 - Frame shear stiffness of welded frames

				Welded frames			
				Sd (kN/rad)		factiles	
Frame load (tons)		Nup		μ	$\sigma = 1000$	5%	95%
	5		25	4000	1000	2000	6000
5	10	25	50	4000	1000	2000	6000
10	20	50	100	6000	1000	4000	8000
20		100		6000	1000	4000	8000

The frame shear stiffness is an important parameter. Since this needs to cover all types it is divided in two frame types:

- Bolted (data provided by Nedcon and SSI Schäfer and confirmed by Peter Stangenberg)
  - The majority of the frames used in Europa is bolted (90%).
  - S_d varies between 300 and 2000 kN/rad
  - S_d with normal distribution and function of frame load
- Welded (data provided by Peter Stangenberg)
  - S_d varies between 2000 and 8000 kN/rad
  - S_d with normal distribution and function of frame load

10.4.11.2Reduced frame shear stiffness

Using the shear flexibility (S_d) only, leads to an overestimation of the internal forces. Therefor the bending flexibility is included in S_d^*.

$$S_D^* = (\frac{h^2}{3\,E\,I} + \frac{1}{S_d})^{-1} \tag{19}$$

$$I = \frac{1}{2} \cdot A_{up} \cdot D_{crs}^2 \tag{20}$$

$$A_{up} = \epsilon \cdot \frac{N_{up}}{f_y} \geq 240 \cdot 1.5 = 360m^2 \tag{21}$$

S_d	frame shear stiffness
S_d^*	reduced frame stiffness including shear and bending flexibility
I	second moment of area of frame
E	young's modulus
A_{up}	upright area
f_y	yield strength
ε	amplification factor (γ_F / χ_{min} = 1.5 / 0.6 = 2.5)

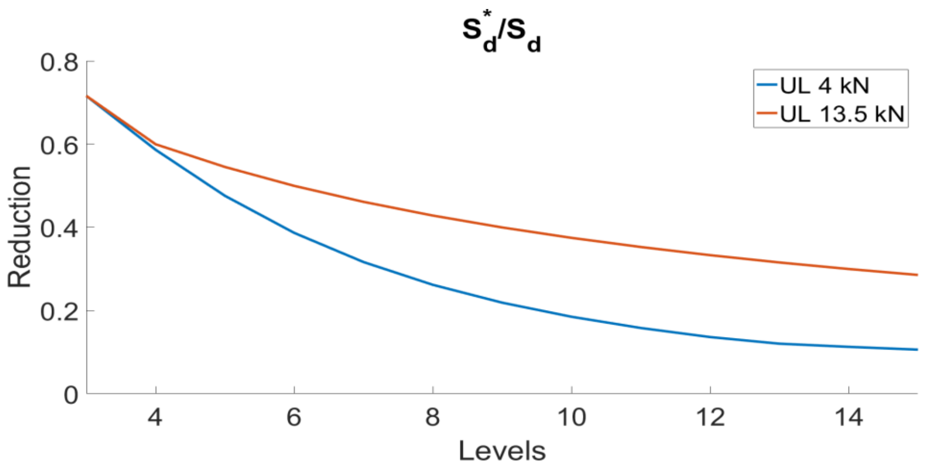


Figure 27 – Accounting for frame bending (in this graph with Sd=1250 kN/rad)

Figure 27 shows that the bending flexibility has a significant influence, especially for the higher frames.

10.4.12 Uncertainty Tolerance

An uncertainty tolerance is added for the same reasoning as for the beam analysis. The uncertainty tolerance distribution is a normal distribution with a mean of: μ = 1.0 and a standard deviation of σ = 0.05. This is conform [2].

10.5 Monte Carlo analysis

The Monte Carlo analysis is divided in two nearly identical calculations. The first bolted 20 cases and the last welded 14 cases. Within each of these calculations there is calculation for the correction factor for the Normal force and one for the shear force in the frame.

For all the cases mentioned in Table 19 and Table 20 the total load effect E is calculated. This is done 100,000 times. An example with all distributions plotted as histogram can be seen in Figure 28 and Figure 29.

- Shear force
  - Manual operated

$$H_i = UT \cdot GL \cdot (Ampl_{man} \cdot ((2 \cdot H_{imp} + 2 \cdot H_{cr} + H_{pl})/2) + H_{slab})$$

  - Automatically operated

$$H_i = UT \cdot GL \cdot (Ampl_{aut} \cdot ((2 \cdot H_{imp} + 2 \cdot H_{cr} + H_{pl}/3)/2) + H_{slab})$$

- Normal force

$$N_i = (\tfrac{1}{8} \cdot \textstyle\sum_{j=1}^{14} UL_{(4j+1)} + \tfrac{3}{8} \cdot \left(\beta \cdot UL_2 + \textstyle\sum_{j=2}^{14} UL_{(4j+2)}\right) + \tfrac{3}{8} \cdot \textstyle\sum_{j=1}^{14} UL_{(4j+3)}$$
$$+ \tfrac{1}{8} \cdot \textstyle\sum_{j=1}^{14} UL_{(4j+4)} + \tfrac{H_i}{UT \cdot GL} \cdot n \cdot \tfrac{\Delta h}{D_{crs}}) \cdot GL_i \cdot UT$$

H_i	Shear load effect from repetition no. i
N_i	Compression load effect from repetition no. i
Ampl	Amplification factor
H_{pl}	Horizontal placement load
H_{imp}	Horizontal imperfection load
H_{slab}	Horizontal load induced by slab rotation
H_{cr}	Horizontal crane load
UL_i	Variable unit load
Imp_z	Imperfection cross aisle
S_d^*	Reduced frame stiffness
Φ_F	Slab rotation in z, as in Table 25
Φ_L	Frame looseness
$\Phi_{1,i}$	Installation angle frame 1 (within looseness range)
$\Phi_{2,i}$	Installation angle frame 2 (within looseness range)

β_{dyn} Dynamic factor for vertical placement applied to UL2

Δh Level height

N Number of levels

D_{crs} Effective frame depth (centre lines)

GL_i Effect of Green level for upright compression load

UT Uncertainty tolerance

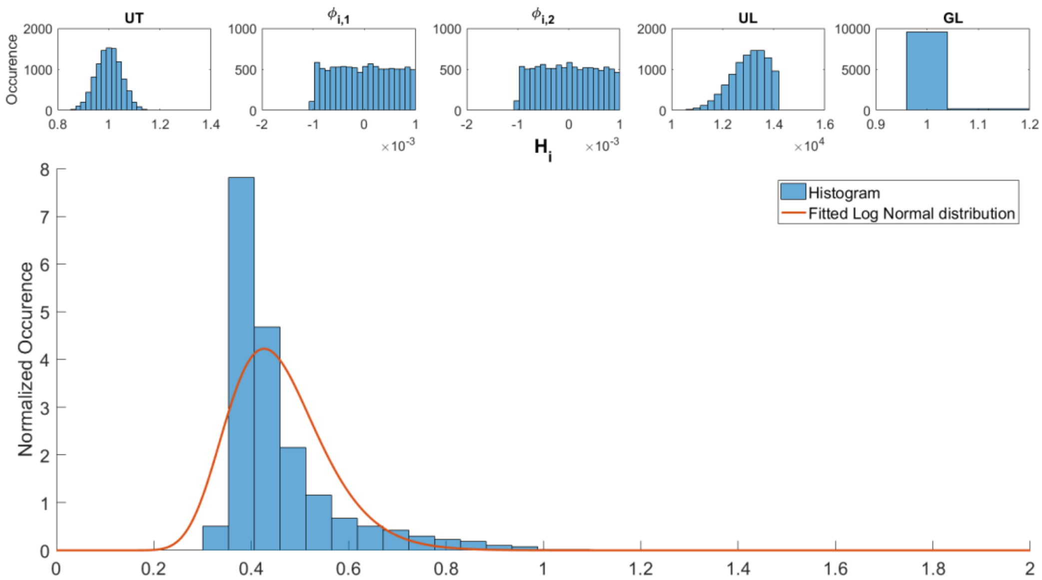


Figure 28 – Example calculation of H for case 1

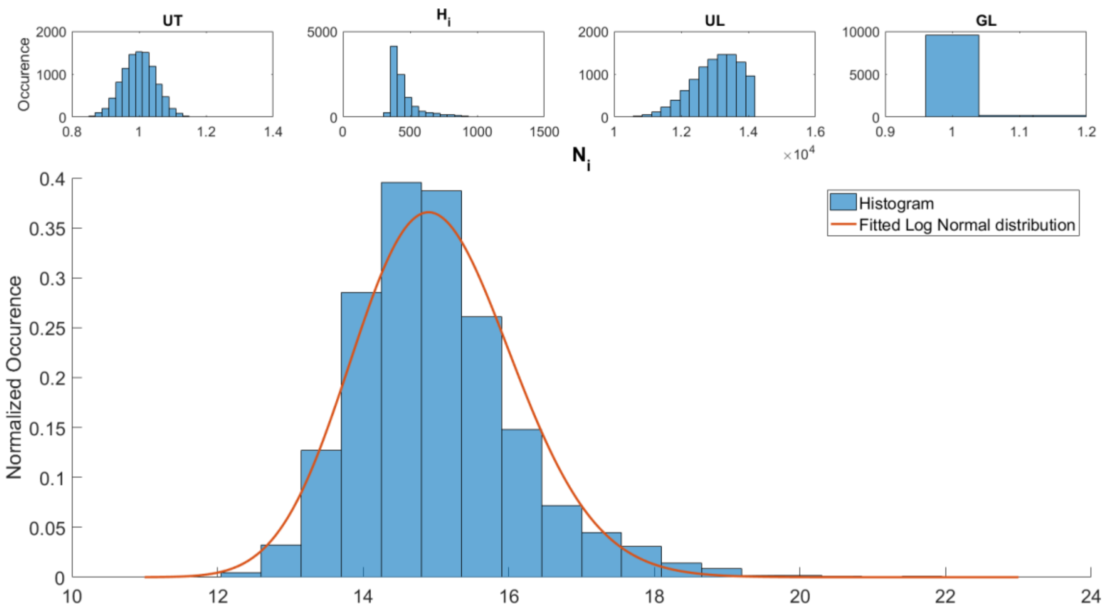


Figure 29 – Example calculation of N for case 1

10.5.1 Results of Monte Carlo

For each of the 34 cases mentioned in Table 19 and Table 20 a Monte Carlo calculation is performed for the Normal and Shear force acting on the frame. A maximum like hood estimation is performed to the results of all cases. This is done for all the 3 distributions mentioned in EN 1990. Respectively; Normal, Lognormal and Gumbel. In Figure 30, Figure 31, Figure 32 and Figure 33 the best fit can be seen.

For simplicity and continuity Log-normal distribution were used. The parameters of these distributions can be found in Figure 28 and Figure 29.

It can be seen that for the Shear forces the Log-normal distribution is the best fit of the three possible distributions although an extreme value distribution would be more appropriate. Since the shear force is not determining the correction factor (it is not the main failure mode) this simplification is acceptable. The parameters of the distributions can be found in Figure 28 and Figure 29.

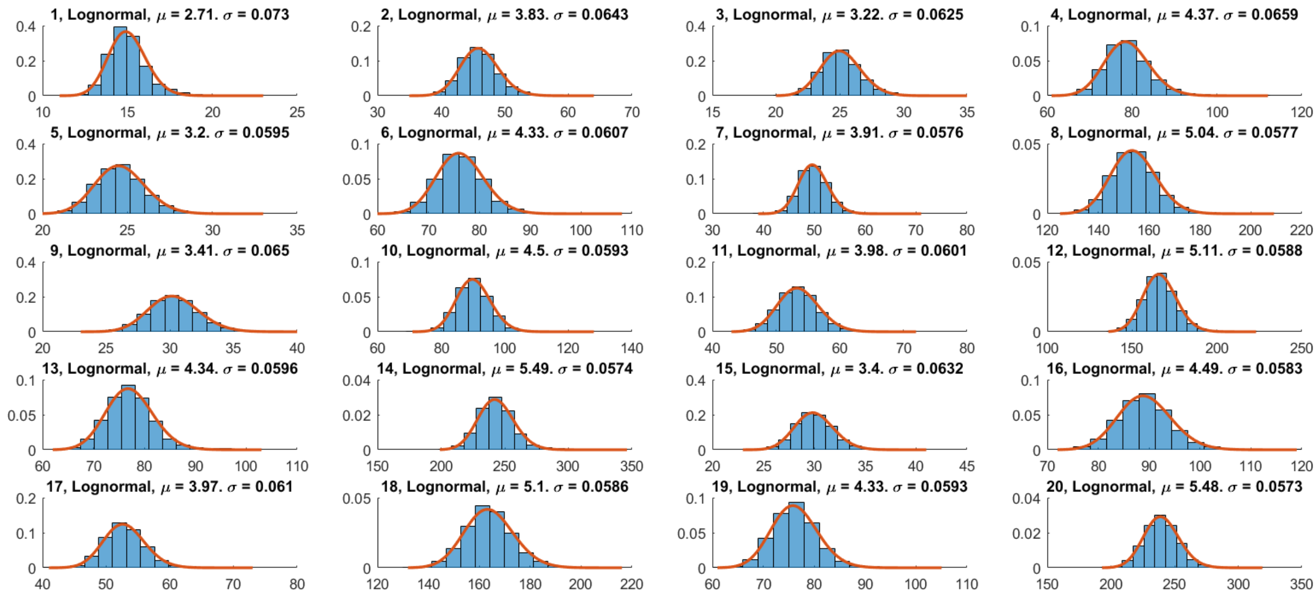


Figure 30 – Normal force results of the bolted 20 cases and a lognormal fit

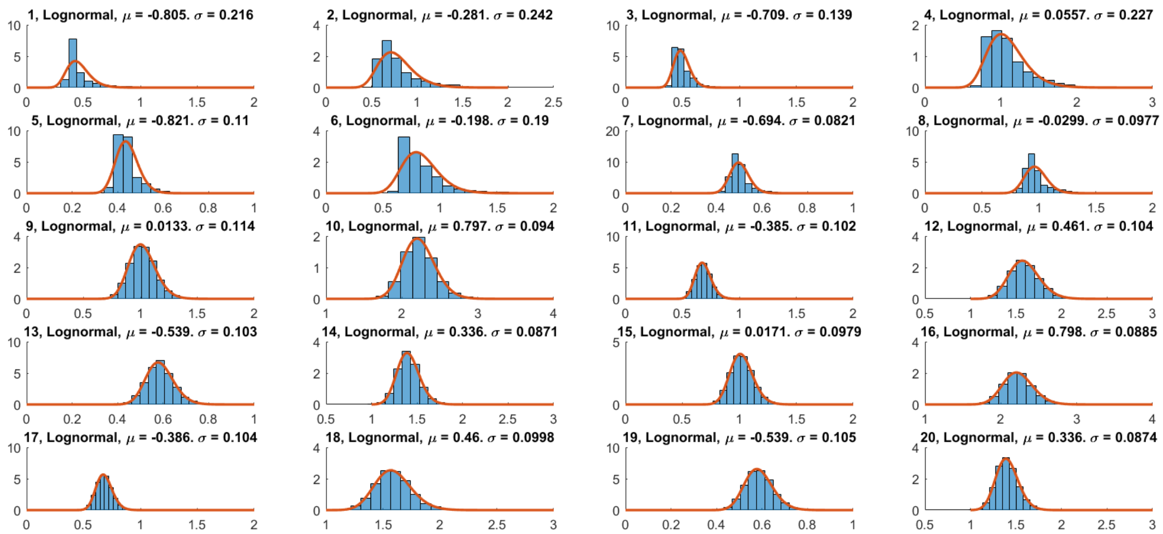


Figure 31 – Shear force results of the bolted 20 cases and a lognormal fit

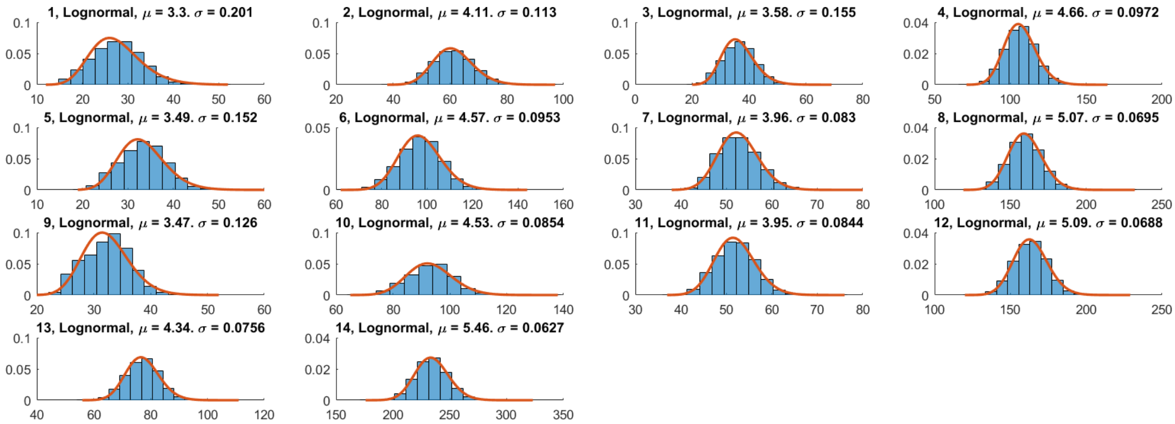


Figure 32 – Normal force results of the welded 14 cases and a lognormal fit

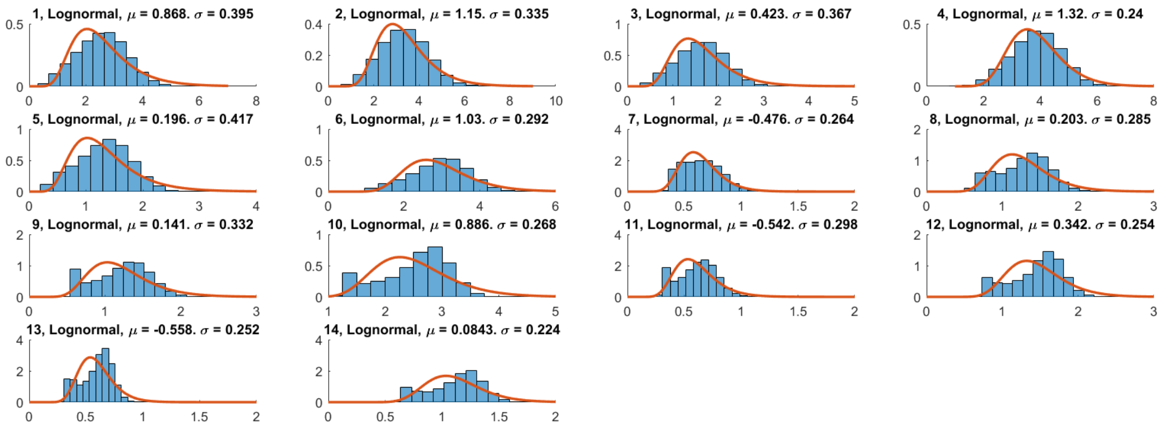


Figure 33 – Shear force results of the welded 14 cases and a lognormal fit

10.6 Design procedure

10.6.1 According to EN 15512:2009

The design load is based on

- pallet loads (UL)
- horizontal placement load (H_{pl})
- horizontal crane load (H_{cr})

10.6.2 Required amendments

10.6.2.1 Design imperfections

The design imperfections are brought in line with EN 1993 and are implemented in prEN 15512:2018. These have been used in the analysis.

10.6.2.2 Floor slab rotation

The slab rotations of Table 18 shall be included in the determination of the correction factor γ_{cor}.

10.6.2.3 Robustness requirement frame bracing

The slab rotation leads to a significant increase of shear forces in the frames. This cannot be compensated by increasing a partial factor. The following is implemented in the prEN 15512:2018;

- For bolted frames
  - The minimum horizontal design force to be considered in the design of the frame bracing shall be the greater of;
    - 1,5 % of the un-factored vertical load in the upright frame
    - 3 kN
- For welded frames
  - N.A.

10.6.3 Combinations

- Normal Force

$E_{specs} = \max(0.9 \cdot [\gamma_l \cdot \gamma_{cor} \cdot UL + (\gamma_l \cdot \gamma_{cor} \cdot H_{imp} / 2 + 1.4 \cdot H_{pl} + 1.5 \cdot H_{cr}) \cdot h/d], \gamma_l \cdot \gamma_{cor} \cdot UL, \gamma_l \cdot \gamma_{cor} \cdot H_{imp} / 2 \cdot h/d, 1.4 \cdot H_{pl} \cdot h/d, 1.5 \cdot H_{cr} \cdot h/d)$

(22)

- Shear Force

$E_{specs} = \max(0.9 \cdot [\gamma_l \cdot \gamma_{cor} \cdot H_{imp} + 1.4 \cdot H_{pl} + 1.5 \cdot H_{cr}], \gamma_l \cdot \gamma_{cor} \cdot H_{imp}, 1.4 \cdot H_{pl}, 1.5 \cdot H_{cr})$ (23)

- The partial load factor γ_l depends on the type of operation
  - For MAN/AUT without weight check, $\gamma_l = 1.4$
  - For AUT with Weight check and refusal, $\gamma_l = 1.3$

10.7 Calculation of the correction factor

Comparing the results of the Monte Carlo analysis with calculated design loads of section 7 a suitable γ_{cor} can be found to meet the target reliability. This is done using equation 24 Table C3 from EN1990. The value for $\alpha = -0.7$ and the value for $\beta = 4.7$ have been taken for RC2 and $\beta = 5.2$ for RC3.

$$\frac{\mu_i \cdot exp(-\alpha \cdot \beta \cdot V_i)}{E_{specs}} \qquad for \qquad V_i = \frac{\sigma_i}{\mu_i} < 0.2$$

(24)

10.7.1 RC2

Figure 34 and Figure 35 show γ_{cor} for all 34 cases. The mean value for the normal force is 1.07.

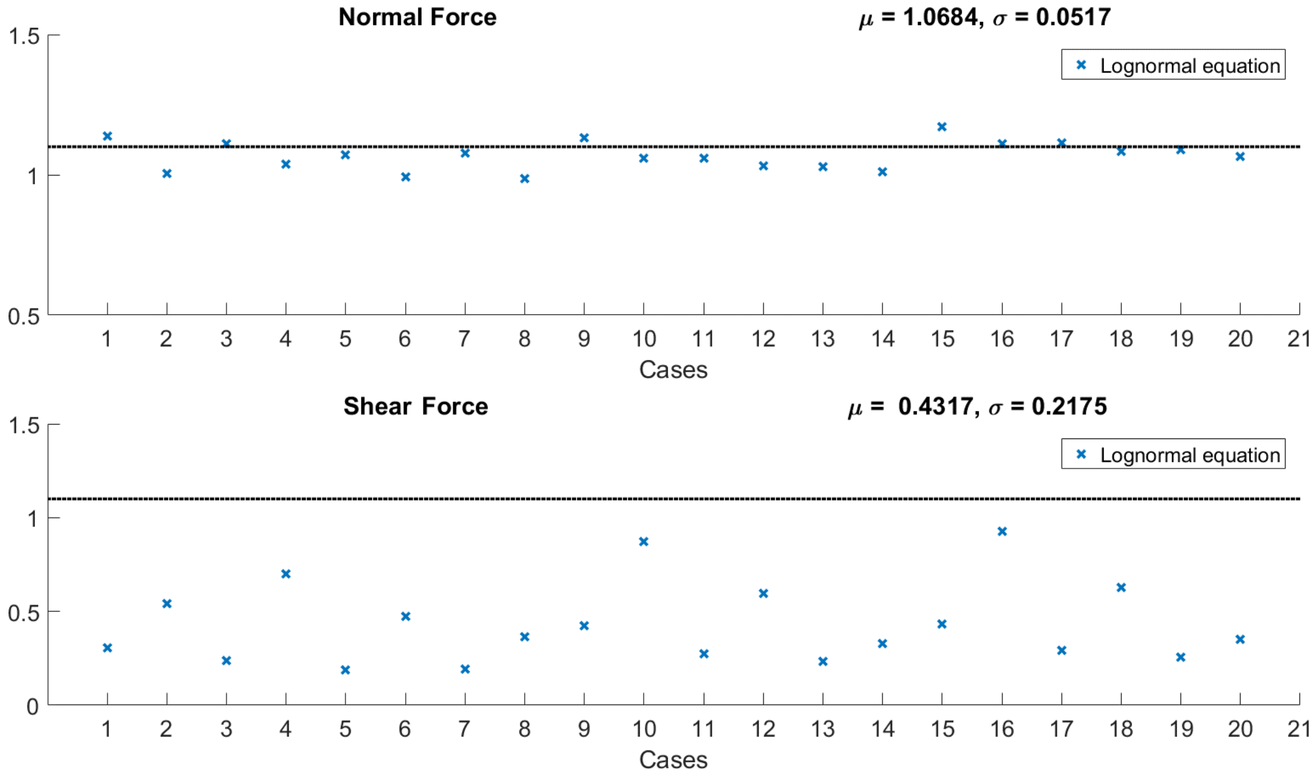


Figure 34 – Results bolted frames for RC2 (case 1 to 20)

For welded frames a significant higher correction factor is needed.

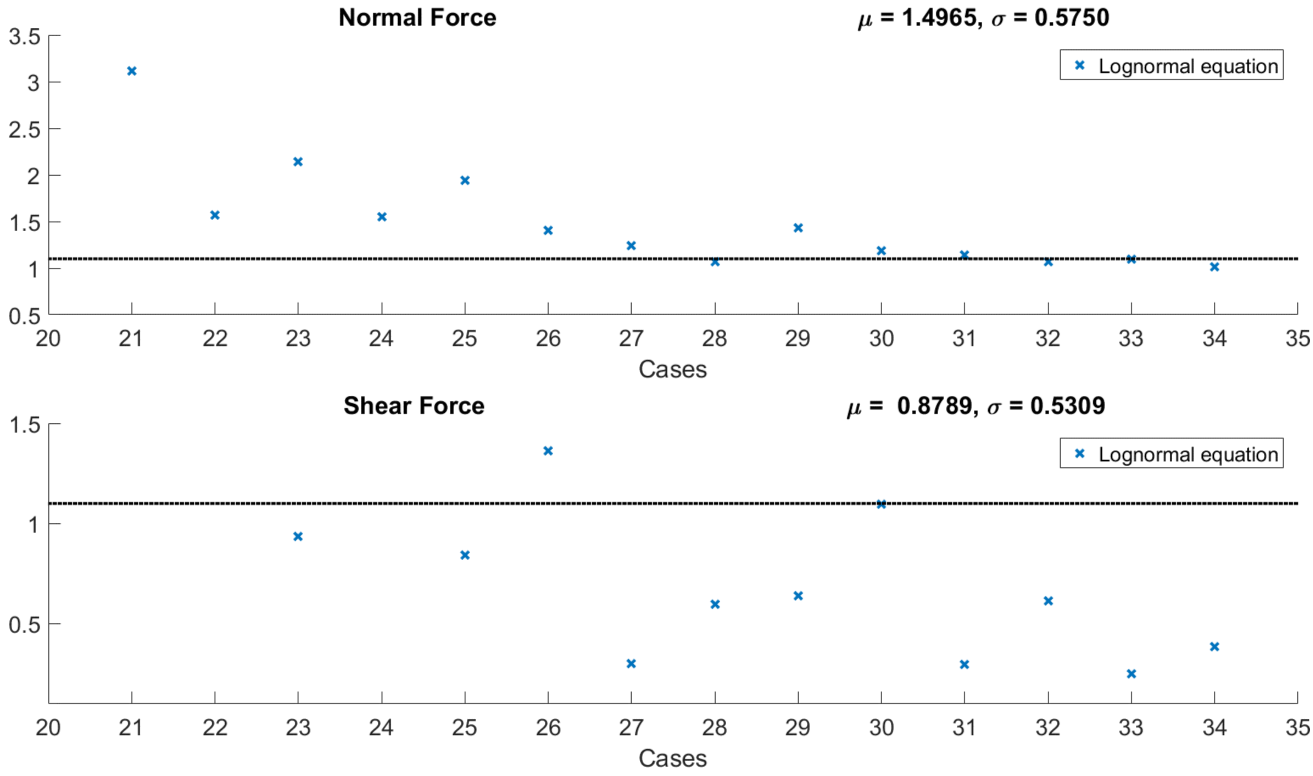


Figure 35 – Results welded frames for RC2 (case 21 to 34)

10.7.2 RC1

Figure 36 and Figure 37 show γ_{cor} for all 34 cases.

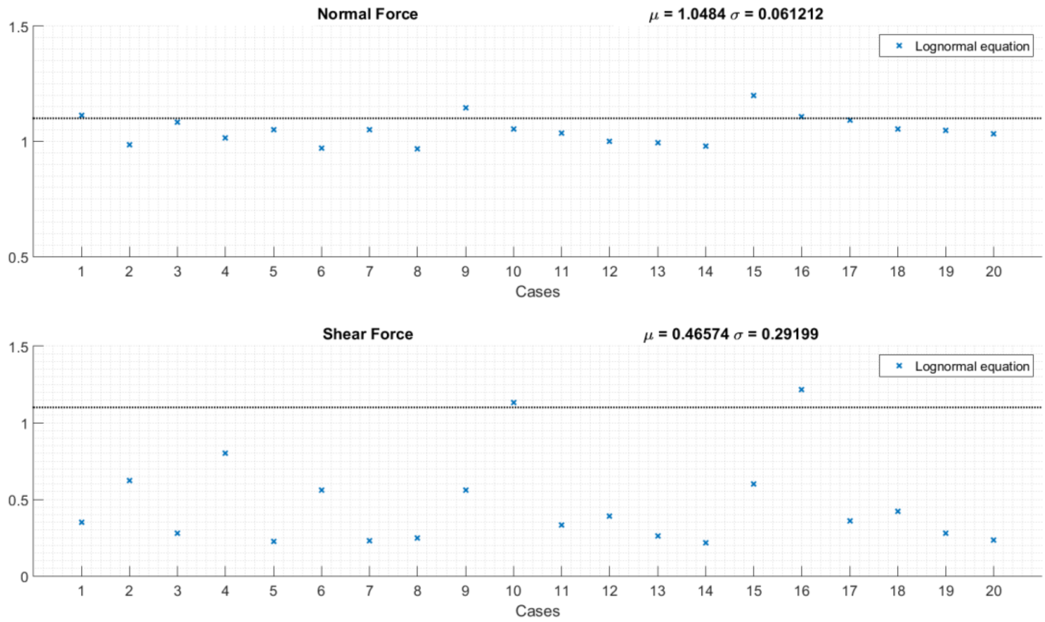


Figure 36 – Results bolted frames for RC1 (case 1 to 20)

For welded frames a significant higher correction factor is needed.

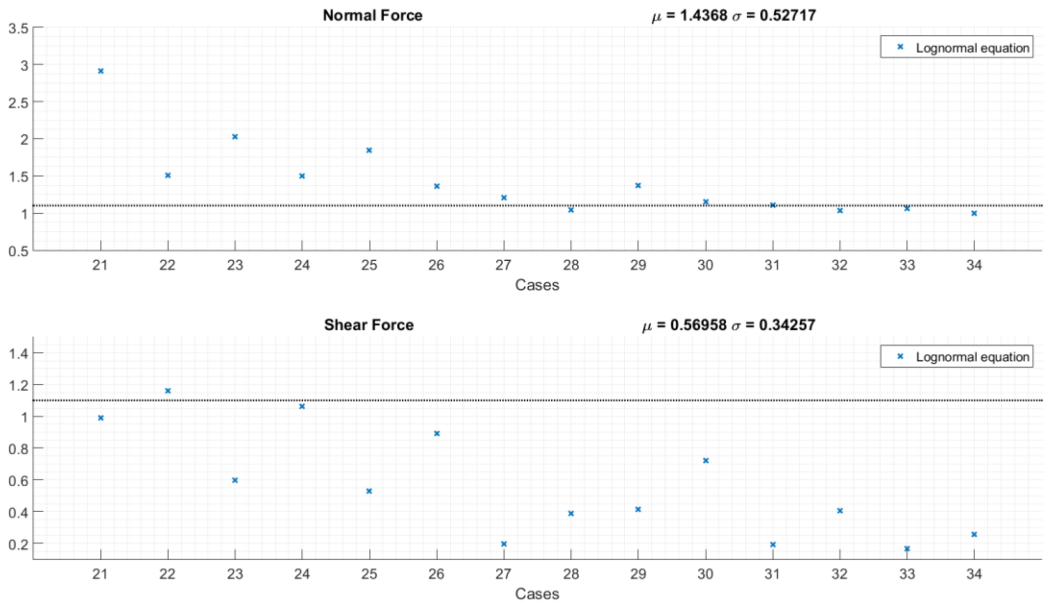


Figure 37 – Results welded frames for RC1 (case 21 to 34)

10.7.3 RC3

Figure 36 and Figure 37 show γ_{cor} for bolted frames.

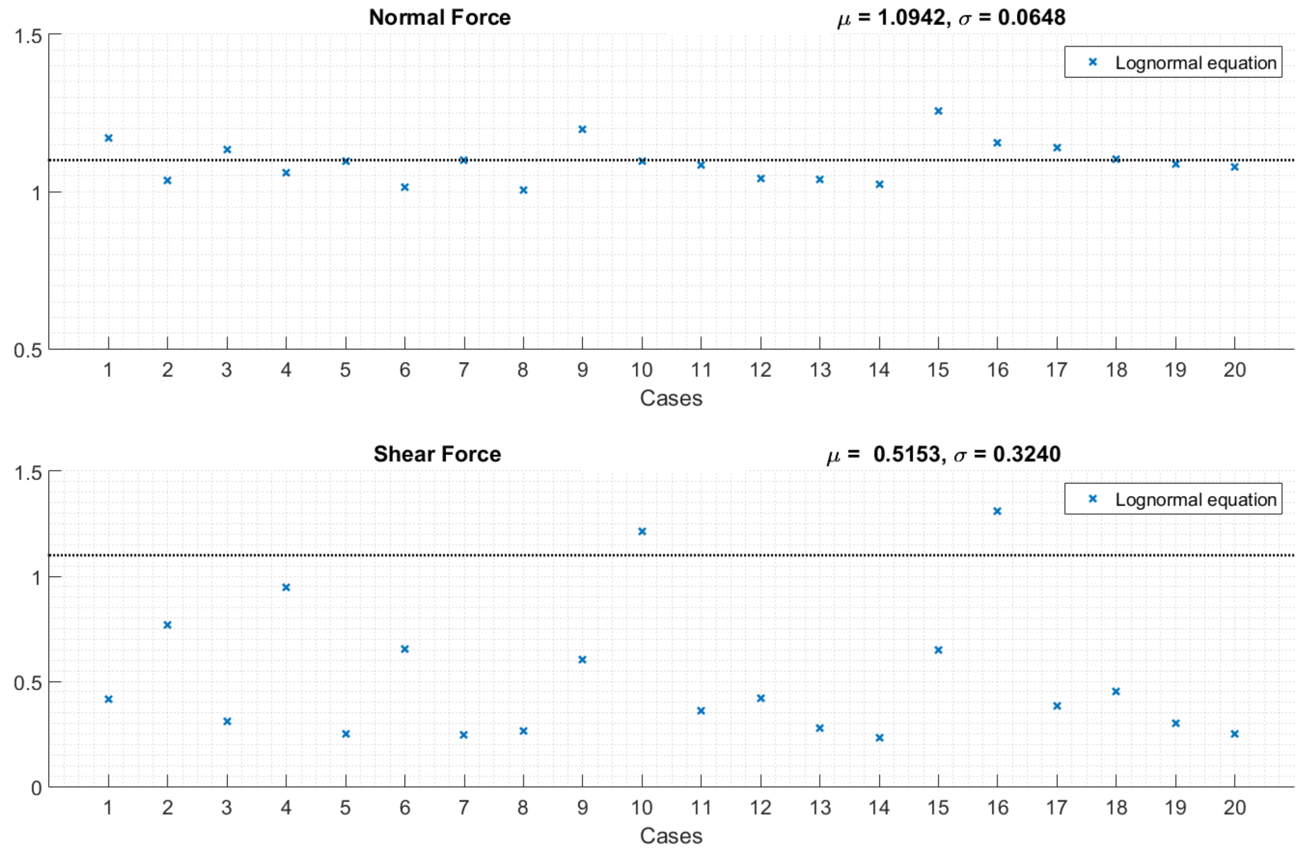


Figure 38 – Results bolted frames for RC3 (case 1 to 20)

For welded frames a significant higher correction factor is needed.

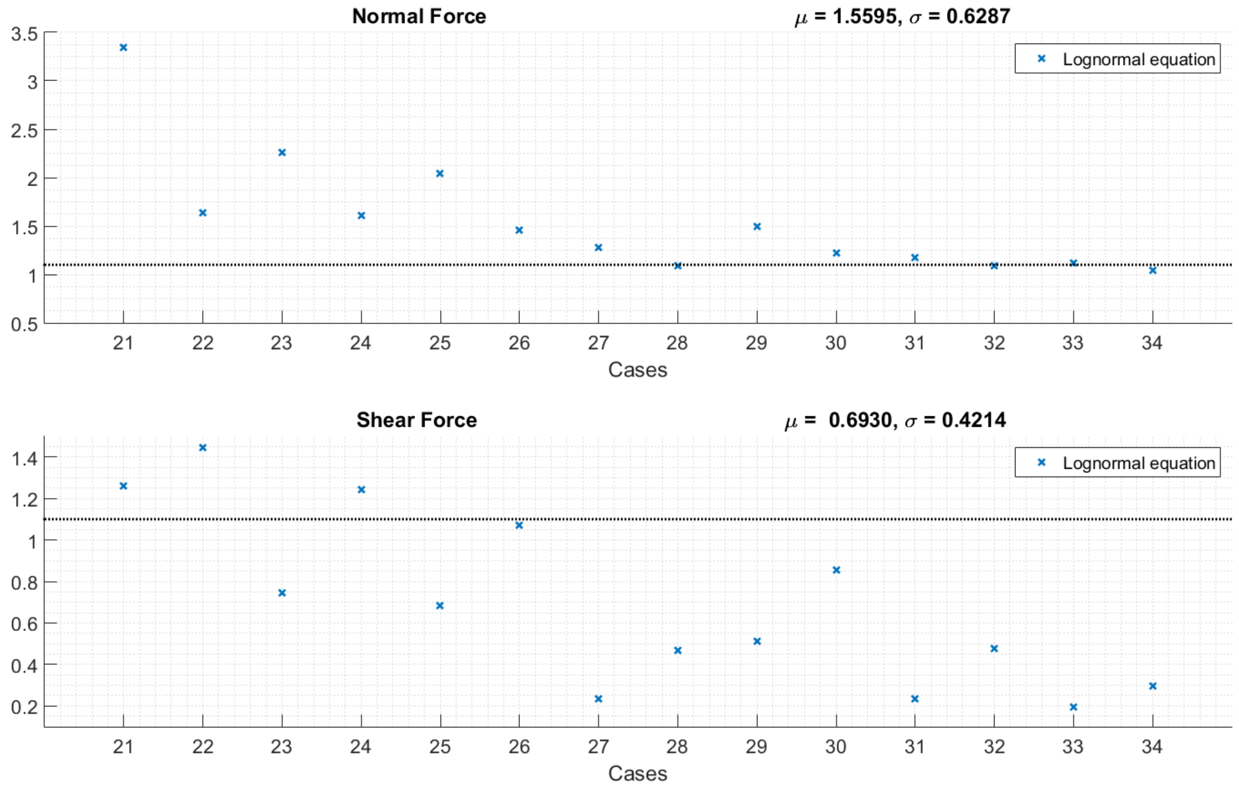


Figure 39 – Results welded frames for RC3 (case 21 to 34)

10.7.4 Exceptional cases for RC2

As mentioned in the previous section there are three cases which with relative high correction factors. The details of these cases can be found in Table 29. Cases exceeding 1.155 are discussed. Since case 15 can be regarded an exceptional case (low and light automated rack with weighing and rejection system) the exceedance is acceptable.

Table 29 - Exceptional cases

		Q_p	Inst. Imp 1/	Φ_F 1/	H	levels	Operation	value
Problem	Case	(kN)	(1/ ..)	(1 / ..)	(m)	n		
Normal	1	4	350	700	6	3	MAN	1.138
Normal	9	4	1000	2000	10	5	AUT	1.129
Normal	15	4	1000	2000	10	5	AUT - W	1.171

10.7.5 Conclusion RC2

For bolted frames, the mean value of γ_{cor} is 1.07. A γ_{cor} =1.10 is proposed.

11 Conclusions

11.1 General

The safety philosophy of EN 15512:2009 does not fulfil the reliability requirement of $\beta \geq 4.7$ for RC2 of EN 1990. This study shows that with the amendment listed in 11.2 and 11.3 the prEN 15512:2018 does meet the target reliability.

11.2 Beams

In order to meet the target reliability for RC2 the following changes to EN 15512:2009 are necessary;

- Improve modelling of pallet load in case of one pallet per compartment (see 9.6.2.2),
- Increase the product of partial factors from $\gamma_I \cdot \gamma_M = 1.4 \cdot 1.0$ to 1.54.

NOTE 1 The proposal for RC1 is a product of partial factors of $\gamma_I \cdot \gamma_M = 1.4 \cdot 1.05 = 1.47$

NOTE 2 The proposal for RC3 is a product of partial factors of $\gamma_I \cdot \gamma_M = 1.4 \cdot 1.15 = 1.61$

11.3 Frames

11.3.1 Bolted frames

In order to meet the target reliability for RC2 the following changes to EN 15512:2009 are necessary;

- Consider slab rotation in excess of Table 18,
- Robustness requirement for the frame bracing (see 10.6.2.3)
- Increase the product of partial factors from $\gamma_I \cdot \gamma_M = 1.4 \cdot 1.0$ to 1.54.
- Add criteria to limit unacceptable stress contributions of allowed eccentricities (see 10.4.9)

NOTE 1 The proposal for RC1 is a product of partial factors of $\gamma_I \cdot \gamma_M = 1.4 \cdot 1.05 = 1.47$

NOTE 2 The proposal for RC3 is a product of partial factors of $\gamma_I \cdot \gamma_M = 1.4 \cdot 1.15 = 1.61$

11.3.2 Welded frames

Due to the possibility of very high frame shear stiffness's, the average correction factor of the defined cases is nearly 1.5. Therefore, the influence of the slab needs to be considered in a separate load case in the design of welded frames.

Annex A **Determination of β_{dynamic}**

Part I

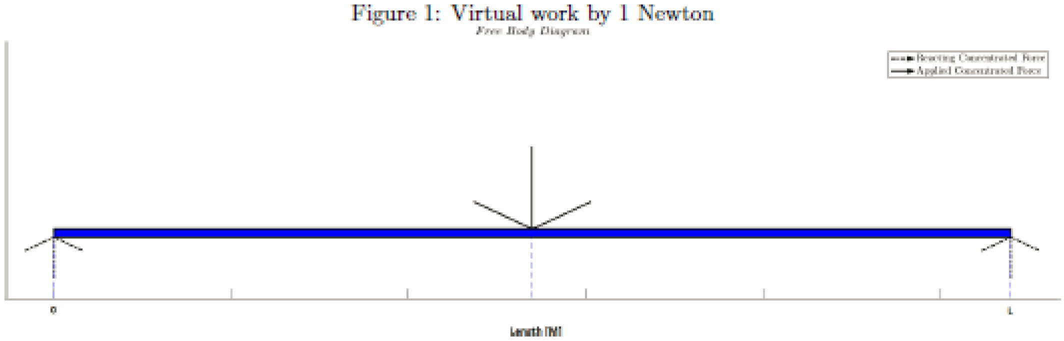
Determining deflection

$$1 \cdot \delta = \int n \frac{N}{EA} dl + \int v \frac{V}{GA_\gamma} dl + \int m \frac{M}{EI} dl + \int t \frac{T}{GJ} dl \quad (1)$$

Assuming normal force, shear force and torsion are negligible small compared to bending moment gives $N, V, , T << M$

$$1 \cdot \delta = \int m \frac{M}{EI} dl \quad (2)$$

Figure 1: Virtual work by 1 Newton



$$\left\{ \begin{array}{cccccc} & Range & & Equations\ of\ Shear\ Force\ [N] & Equations\ of\ Bending\ Moment\ [N/m] \\ 0 & < x \leq & \frac{1}{2} \cdot L & 0.5 & 0.5 \cdot x \\ \frac{1}{2} \cdot L & < x \leq & L & -0.5 & -0.5 \cdot x + 0.5 \cdot L \end{array} \right\} \quad (3)$$

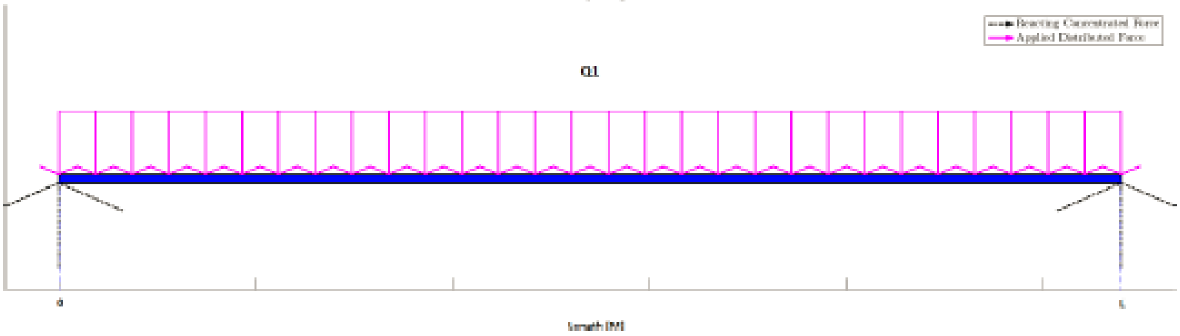
$$\delta_{moment} = Bending\ Moment\ Virtual\ work \cdot Bending\ Moment\ situation \quad (4)$$

$$\delta = \frac{1}{E \cdot I} \int_0^L \delta_{moment}\ dx \quad (5)$$

One pallet per compartment

Situation 1

Figure 2: Situation δ_1
Free Body Diagram



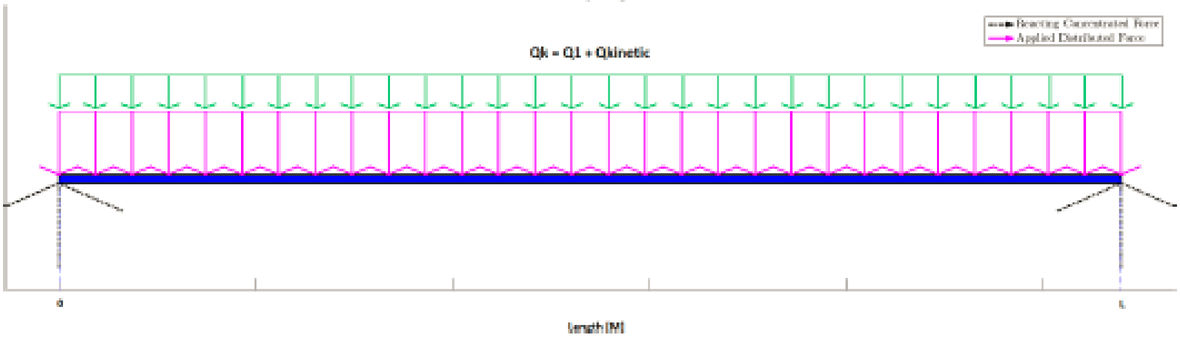
$$\left\{\begin{array}{llll} & Range & Equations\ of\ Shear\ Force\ [N] & Equations\ of\ Bending\ Moment\ [N/m] \\ 0 & < x \leq \quad L & \frac{1}{2}q_1 L - q_1 x & \frac{1}{2}q_1 L x - \frac{1}{2}q_1 x^2 \end{array}\right\} \tag{6}$$

$$U = \int \left(\frac{M^2}{2EI}\right) dx \tag{7}$$

$$U_{potential} = \frac{L^5\, \mathrm{q1}^2}{240\, E\, I} \tag{8}$$

Situation 2

Figure 3: Situation δ_2
Free Body Diagram



Equations

$$q_k = \frac{\sqrt{L^5\, \mathrm{q1}^2 + 120\, E\, I\, \mathrm{m2}\, v^2}}{L^{\frac{5}{2}}} \tag{9}$$

$$\delta_1 = \frac{5\, L^4\, \mathrm{q1}}{384\, E\, I} \tag{10}$$

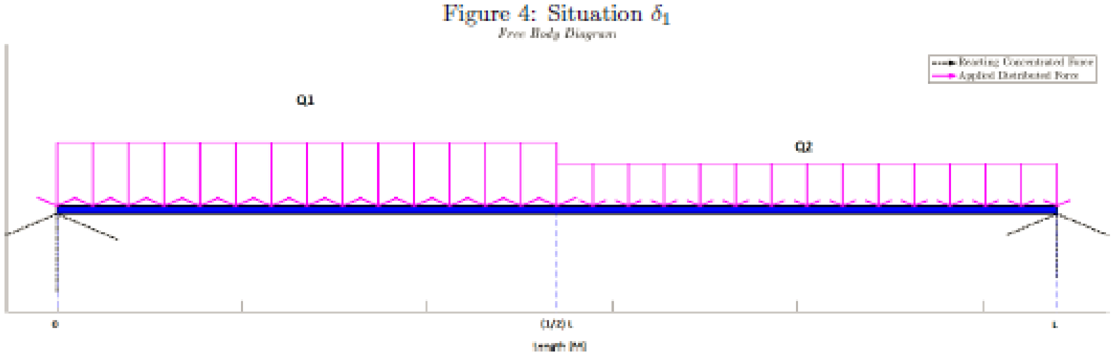
$$\delta_2 = \frac{5\, L^{\frac{3}{2}}\, \sqrt{L^5\, \mathrm{q1}^2 + 120\, E\, I\, \mathrm{m2}\, v^2}}{384\, E\, I} \tag{11}$$

$$\beta = \frac{\sqrt{L^5\, \mathrm{q1}^2 + 120\, E\, I\, \mathrm{m2}\, v^2}}{L^{\frac{5}{2}}\, \mathrm{q1}} \tag{12}$$

Two pallets per compartment

Situation 1

Figure 4: Situation δ_1



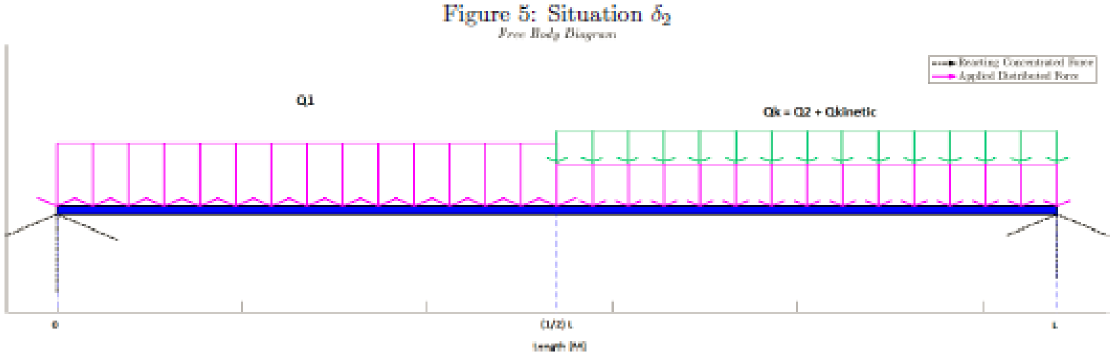
$$\left\{ \begin{array}{lllcc} & Range & & Equations\ of\ Shear\ Force\ [N] & Equations\ of\ Bending\ Moment\ [N/m] \\ 0 & < x \leq & \frac{1}{2}\cdot L & \frac{3\,L\,\mathrm{q1}}{8}+\frac{L\,\mathrm{q2}}{8}-\mathrm{q1}\,x & x\left(\frac{3\,L\,\mathrm{q1}}{8}+\frac{L\,\mathrm{q2}}{8}\right)-\frac{\mathrm{q1}\,x^2}{2} \\ \frac{1}{2}\cdot L & < x \leq & L & \frac{5\,L\,\mathrm{q2}}{8}-\frac{L\,\mathrm{q1}}{8}-\mathrm{q2}\,x & \frac{(L-x)\,(L\,\mathrm{q1}-L\,\mathrm{q2}+4\,\mathrm{q2}\,x)}{8} \end{array} \right\} \tag{13}$$

$$U=\int\left(\frac{M^2}{2EI}\right)dx \tag{14}$$

$$U_{potential}=\frac{L^5\,\left(17\,\mathrm{q1}^2+30\,\mathrm{q1}\,\mathrm{q2}+17\,\mathrm{q2}^2\right)}{15360\,E\,I} \tag{15}$$

Situation 2

Figure 5: Situation δ_2



Equations

$$q_k=\frac{\sqrt{225\,L^{10}\,\mathrm{q1}^2+510\,L^{10}\,\mathrm{q1}\,\mathrm{q2}+289\,L^{10}\,\mathrm{q2}^2+130560\,E\,I\,\mathrm{m2}\,L^5\,v^2}-15\,L^5\,\mathrm{q1}}{17\,L^5} \tag{16}$$

$$\delta_1=\frac{5\,L^4\,(\mathrm{q1}+\mathrm{q2})}{768\,E\,I} \tag{17}$$

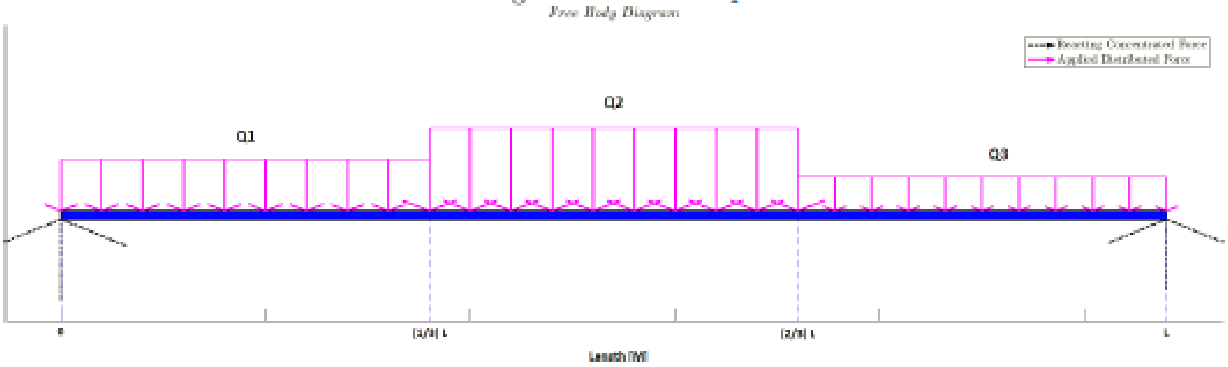
$$\delta_2=\frac{5\,L^5\,\mathrm{q1}+\frac{5\,\sqrt{L^5\,(225\,L^5\,\mathrm{q1}^2+510\,L^5\,\mathrm{q1}\,\mathrm{q2}+289\,L^5\,\mathrm{q2}^2+130560\,E\,I\,\mathrm{m2}\,v^2)}}{2}}{6528\,E\,I\,L} \tag{18}$$

$$\beta=\frac{\sqrt{225\,L^{10}\,\mathrm{q1}^2+510\,L^{10}\,\mathrm{q1}\,\mathrm{q2}+289\,L^{10}\,\mathrm{q2}^2+130560\,E\,I\,\mathrm{m2}\,L^5\,v^2}+2\,L^5\,\mathrm{q1}}{17\,L^5\,\mathrm{q1}+17\,L^5\,\mathrm{q2}} \tag{19}$$

Three pallets per compartment

Situation 1

Figure 6: Situation δ_1



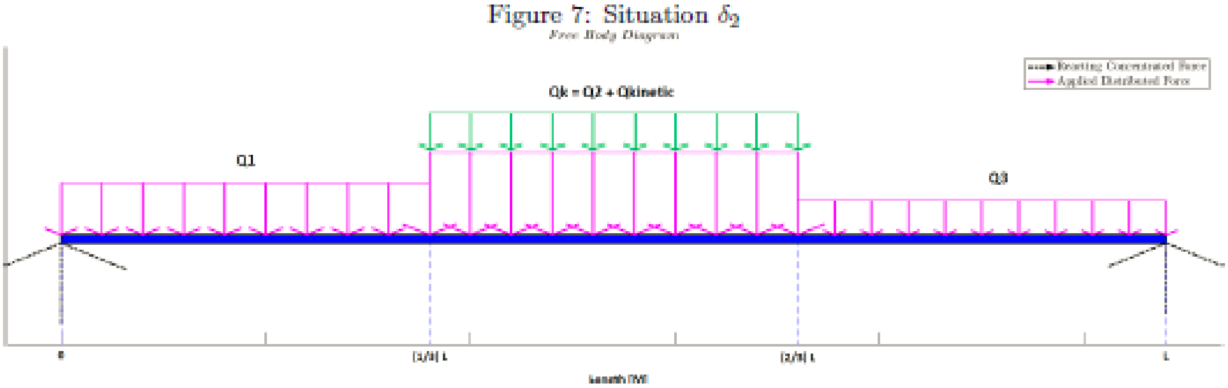
$$\left\{\begin{array}{lllccc} & Range & & Equations\ of\ Shear\ Force\ [N] & Equations\ of\ Bending\ Moment\ [N/m] \\ 0 & < x \leq & \frac{1}{3}\cdot L & \frac{5\,L\,q1}{18}+\frac{L\,q2}{6}+\frac{L\,q3}{18}-q1\,x & x\left(\frac{5\,L\,q1}{18}+\frac{L\,q2}{6}+\frac{L\,q3}{18}\right)-\frac{q1\,x^2}{2} \\ \frac{1}{3}\cdot L & < x \leq & \frac{2}{3}\cdot L & \frac{L\,q2}{2}-\frac{L\,q1}{18}+\frac{L\,q3}{18}-q2\,x & \frac{L^2\,q1}{18}-\frac{L^2\,q2}{18}-\frac{q2\,x^2}{2}-\frac{L\,q1\,x}{18}+\frac{L\,q2\,x}{2}+\frac{L\,q3\,x}{18} \\ \frac{2}{3}\cdot L & < x \leq & L & \frac{13\,L\,q3}{18}-\frac{L\,q2}{6}-\frac{L\,q1}{18}-q3\,x & \frac{(L-x)\,(L\,q1+3\,L\,q2-4\,L\,q3+9\,q3\,x)}{18} \end{array}\right\} \tag{20}$$

$$U = \int\left(\frac{M^2}{2EI}\right)dx \tag{21}$$

$$U_{potential} = \frac{L^5\,\left(53\,q1^2+175\,q1\,q2+85\,q1\,q3+186\,q2^2+140\,q2\,q3+90\,q3^2\right)}{174960\,E\,I} \tag{22}$$

Situation 2

Figure 7: Situation δ_2



Equations

$$q_k = -\frac{5\left(35\,L^5\,\mathrm{q1} - \frac{\sqrt{L^5\,(30625\,L^5\,\mathrm{q1}^2 + 130200\,L^5\,\mathrm{q1}\,\mathrm{q2} + 49000\,L^5\,\mathrm{q1}\,\mathrm{q3} + 138384\,L^5\,\mathrm{q2}^2 + 104160\,L^5\,\mathrm{q2}\,\mathrm{q3} + 19600\,L^5\,\mathrm{q3}^2 + 6508512\,0\,E\,I\,\mathrm{m2}\,v^2)}}{5} + 28\,L^5\,\mathrm{q3}\right)}{372\,L^5} \tag{23}$$

$$\delta_1 = \frac{5\,L^4\,(20\,\mathrm{q1} + 41\,\mathrm{q2} + 20\,\mathrm{q3})}{31104\,E\,I} \tag{24}$$

$$\delta_2 = \frac{1325\,L^5\,\mathrm{q1} + 8500\,L^5\,\mathrm{q3} + 205\,\sqrt{30625\,L^{10}\,\mathrm{q1}^2 + 130200\,L^{10}\,\mathrm{q1}\,\mathrm{q2} + 49000\,L^{10}\,\mathrm{q1}\,\mathrm{q3} + 138384\,L^{10}\,\mathrm{q2}^2 + 104160\,L^{10}\,\mathrm{q2}\,\mathrm{q3} + 19600\,L^{10}\,\mathrm{q3}^2 + 65085120\,E\,I\,\mathrm{m2}\,L^5\,v^2}}{11570688\,E\,I\,L} \tag{25}$$

$$\beta = \frac{265\,L^5\,\mathrm{q1} + 1700\,L^5\,\mathrm{q3} + 41\,\sqrt{30625\,L^{10}\,\mathrm{q1}^2 + 130200\,L^{10}\,\mathrm{q1}\,\mathrm{q2} + 49000\,L^{10}\,\mathrm{q1}\,\mathrm{q3} + 138384\,L^{10}\,\mathrm{q2}^2 + 104160\,L^{10}\,\mathrm{q2}\,\mathrm{q3} + 19600\,L^{10}\,\mathrm{q3}^2 + 65085120\,E\,I\,\mathrm{m2}\,L^5\,v^2}}{7440\,L^5\,\mathrm{q1} + 15252\,L^5\,\mathrm{q2} + 7440\,L^5\,\mathrm{q3}} \tag{26}$$

$$q1 = \frac{3\,g\,\mathrm{m1}}{L}, \qquad q2 = \frac{3\,g\,\mathrm{m2}}{L}, \qquad q3 = \frac{3\,g\,\mathrm{m3}}{L} \tag{27}$$

$$q_k = -\frac{175\,L^4\,g\,\mathrm{m1} - \sqrt{L^5\,\left(30625\,L^3\,g^2\,\mathrm{m1}^2 + 130200\,L^3\,g^2\,\mathrm{m1}\,\mathrm{m2} + 49000\,L^3\,g^2\,\mathrm{m1}\,\mathrm{m3} + 138384\,L^3\,g^2\,\mathrm{m2}^2 + 104160\,L^3\,g^2\,\mathrm{m2}\,\mathrm{m3} + 19600\,L^3\,g^2\,\mathrm{m3}^2 + 28926720\,E\,I\,\mathrm{m2}\,v^2\right)} + 140\,L^4\,g\,\mathrm{m3}}{248\,L^5} \tag{28}$$

$$\delta_1 = \frac{5\,L^3\,g\,(20\,\mathrm{m1} + 41\,\mathrm{m2} + 20\,\mathrm{m3})}{20736\,E\,I} \tag{29}$$

$$\delta_2 = \frac{205\,\sqrt{L^5\,\left(30625\,L^3\,g^2\,\mathrm{m1}^2 + 130200\,L^3\,g^2\,\mathrm{m1}\,\mathrm{m2} + 49000\,L^3\,g^2\,\mathrm{m1}\,\mathrm{m3} + 138384\,L^3\,g^2\,\mathrm{m2}^2 + 104160\,L^3\,g^2\,\mathrm{m2}\,\mathrm{m3} + 19600\,L^3\,g^2\,\mathrm{m3}^2 + 28926720\,E\,I\,\mathrm{m2}\,v^2\right)} + 1325\,L^4\,g\,\mathrm{m1} + 8500\,L^4\,g\,\mathrm{m3}}{7713792\,E\,I\,L} \tag{30}$$

$$\beta = \frac{41\,\sqrt{L^5\,\left(30625\,L^3\,g^2\,\mathrm{m1}^2 + 130200\,L^3\,g^2\,\mathrm{m1}\,\mathrm{m2} + 49000\,L^3\,g^2\,\mathrm{m1}\,\mathrm{m3} + 138384\,L^3\,g^2\,\mathrm{m2}^2 + 104160\,L^3\,g^2\,\mathrm{m2}\,\mathrm{m3} + 19600\,L^3\,g^2\,\mathrm{m3}^2 + 28926720\,E\,I\,\mathrm{m2}\,v^2\right)} + 265\,L^4\,g\,\mathrm{m1} + 1700\,L^4\,g\,\mathrm{m3}}{372\,L^4\,g\,(20\,\mathrm{m1} + 41\,\mathrm{m2} + 20\,\mathrm{m3})} \tag{31}$$

Comparison between Analytical model & Test results

To determine if the analytical model gives a correct representation of the dynamic factor β, NEDCON has conducted a series of drop-test with a three- and one-pallet per compartment configuration. The results are presented in the section below.

Dissipation Factor

The purpose of the drop-test was to determine the correlation between the analytical equations 12 and 32 and reality. A test setup was devised which was capable of drop-testing a pallet onto a beam. [1] [2]. The beam properties were changed to identify the influence of the number of pallets per compartment on the dynamic factor β. The properties used can be seen in table 1 and 2.

Table 1: Data for tests preformed by NEDCON - One pallet per compartment

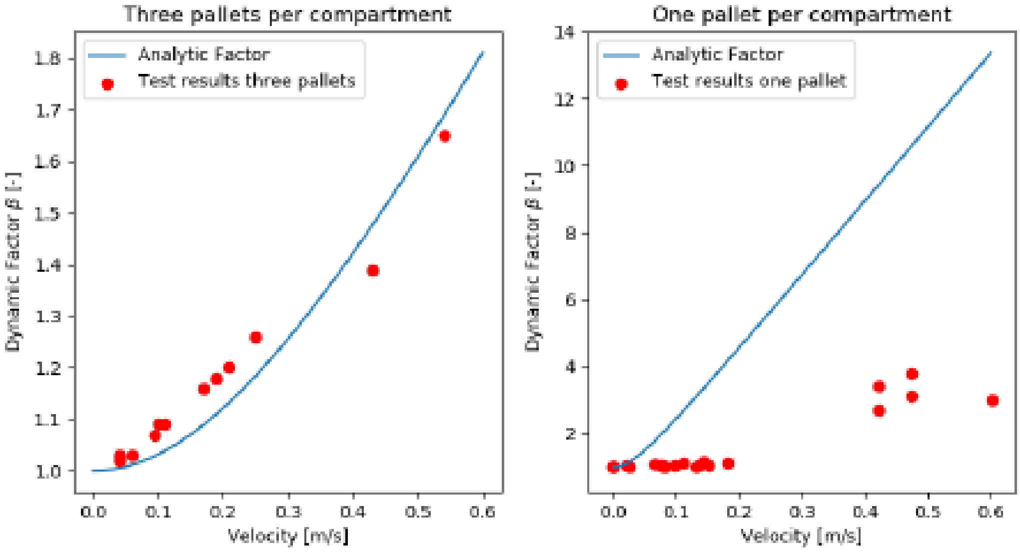
I_{1-test}	=	$1.313 \cdot 10^{-6}$	[m^4]	E	=	$207 \cdot 10^9$	[pa]
M1	=	800	[kg]	L	=	0.95	[m]

Table 2: Data for tests preformed by NEDCON - Three pallets per compartment

I_{3-test}	=	$3.167 \cdot 10^{-6}$	[m^4]	E	=	$207 \cdot 10^9$	[pa]
M2	=	800	[kg]	L	=	2.74	[m]

Figure 8 compares the experimental data to the lines created by plotting equations 12 and 32, with parameters from tables 1 and 2, with respect to a varying velocity. No significant differences were found between the analytical model for three pallets per compartment and the test data. On the other hand, the results for the one pallet per compartment test, indicate that not all the kinetic energy is converted to potential energy stored in the beam. Due to the relative high stiffness of the short beam, it is assumed that a significant portion of the energy is dissipated.

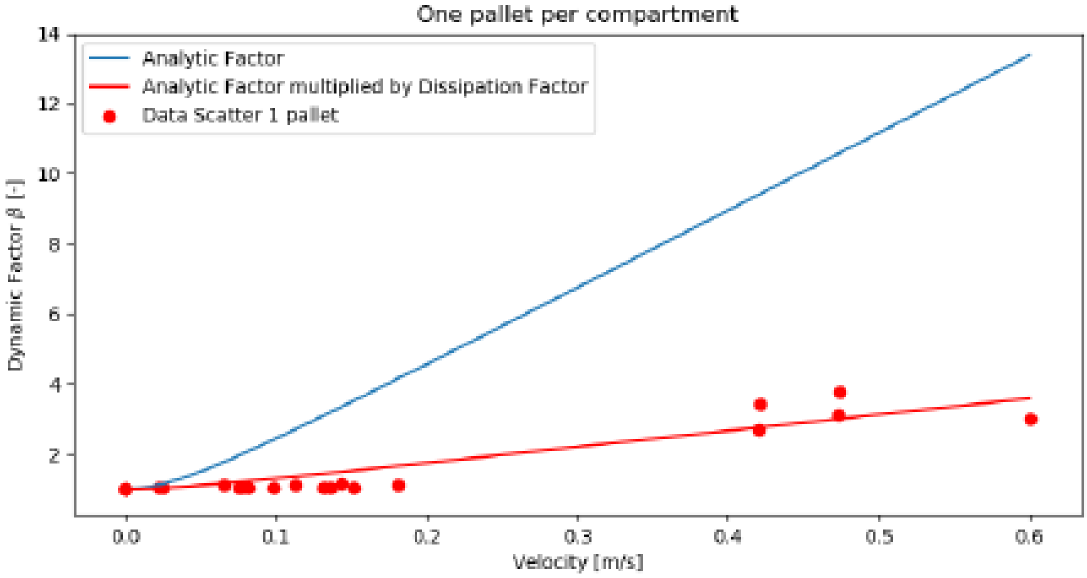
Figure 8: Comparison between analytical solution and test results for 3 and 1 pallets per compartment



A dissipation factor (DF) as defined in equation 33 is sought to match the one pallet per compartment test data with the analytical model. With a minimisation process (root mean square error) a DF of 0.209 was found. The plotted analytical factor adjusted with the DF, can be seen in figure 9

$$\beta_{disipated} = DF \cdot (\beta_{dynamic} - 1) + 1 \tag{33}$$

Figure 9: Three pallets per compartment - Analytical calculation scaled with dissipation factor DF = 0.209



Counter-intuitively the found dissipation factor of 0.209, seems relatively low if judged from an engineering approach. To find an explanation for this thought-provoking behaviour, a comparison was made between the stiffness requirement of the cases used in the Monte Carlo analysis and the second moment of area of the beams. This comparison can be seen in table 3. The value for I_c is defined according to equation 35 which follows from equation 34.

$$\delta_{max} = \frac{1}{300} \cdot L = \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I_c} \tag{34}$$

$$I_c = \frac{1500 \cdot q \cdot L^3}{384 \cdot E} \tag{35}$$

Table 3: Comparison between second moment of area of test and stiffness requirement

I_{1-test}	=	$1.313 \cdot 10^{-6}$	[m^4]	I_{c1}	=	$1.337 \cdot 10^{-7}$	[m^4]	I_{1-test}/I_{c1}	=	9.83	[-]
I_{3-test}	=	$3.167 \cdot 10^{-6}$	[m^4]	I_{c3}	=	$3.239 \cdot 10^{-6}$	[m^4]	I_{3-test}/I_{c3}	=	0.98	[-]

The stiffness comparison results had a remarkable outcome. The three pallet per compartment beam had a second moment of area which was matching with its stiffness requirement. The one pallet per compartment beam had a second moment of area which was a multitude of what was required by its stiffness requirement. Therefore the analytical calculted factor β needed to be corrected. It can be seen in equation 12 that the dynamic factor β is proportional to the square root of the second moment of area. Therefore the found dissipation factor of 0.209 needs to be corrected for the "too stiff" beam. This correction can be seen in equation 36. Because the analytical model already matches the test data for three pallets per compartment, a dissipation factor of 1 is assumed for this cases. The dissipation factor DF for two pallets per compartment is conservatively assumed 1.

$$DF_1 = 0.209 \cdot \sqrt{9.83} = 0.64 \tag{36}$$

Table 4: DF for all pallets per compartments

$DF_{1-Pallet}$	=	0.64	[-]
$DF_{2-Pallet}$	=	1	[-]
$DF_{3-Pallet}$	=	1	[-]

Annex B **Clarifying pictures of frame types and frame levels**

Table 30 - Two different types of frames

Bolted Frames	Welded Frames
	

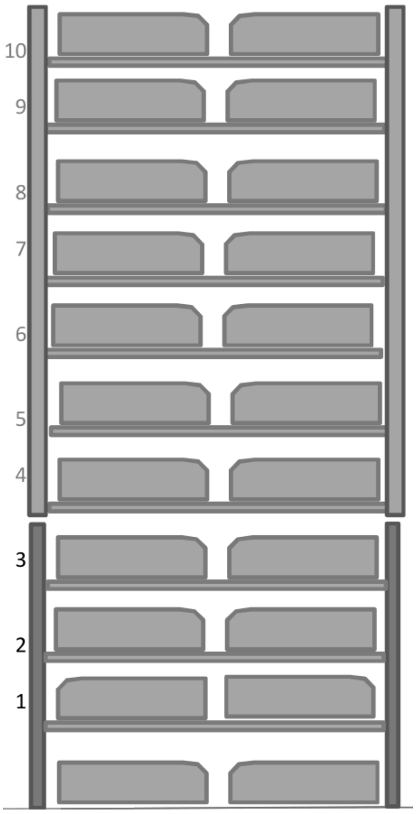
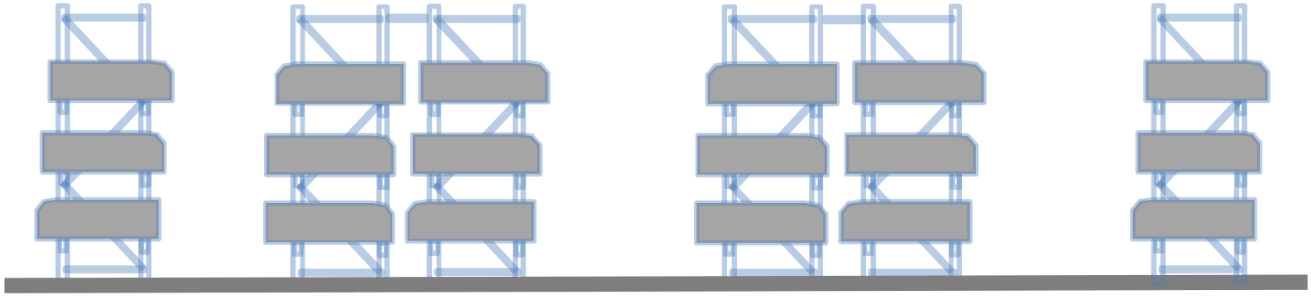
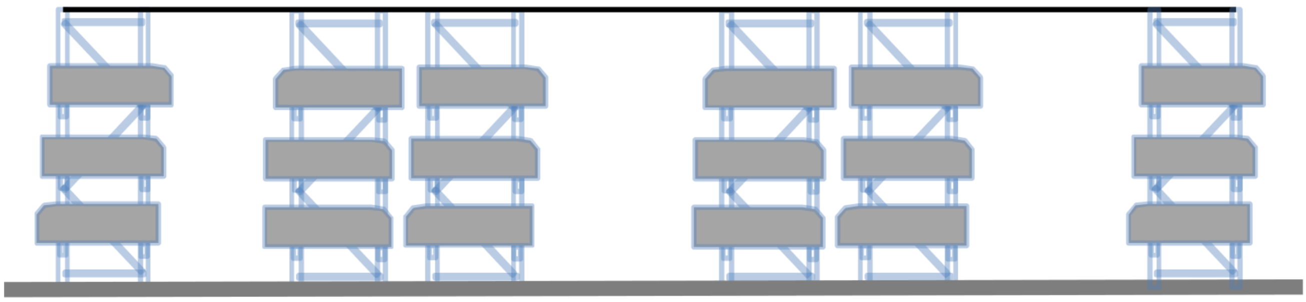


Figure 40 – Overview of frame level definition



Manual operated APR; not connected at the top in cross-aisle direction



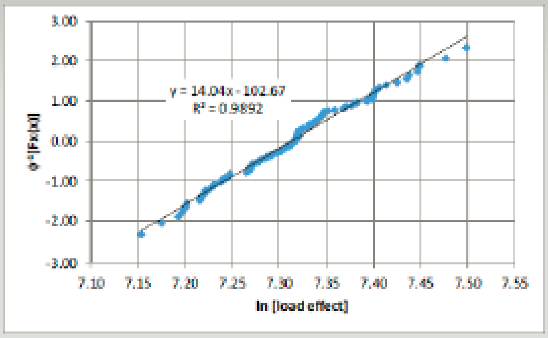
Automatic operated APR; connected at the top in cross-aisle direction

Figure 41 – Frame top connection

Annex C **Usage of α conform EN1990**

A) Standard deviation of the load effect side

Statistical parameters of pallet weights:

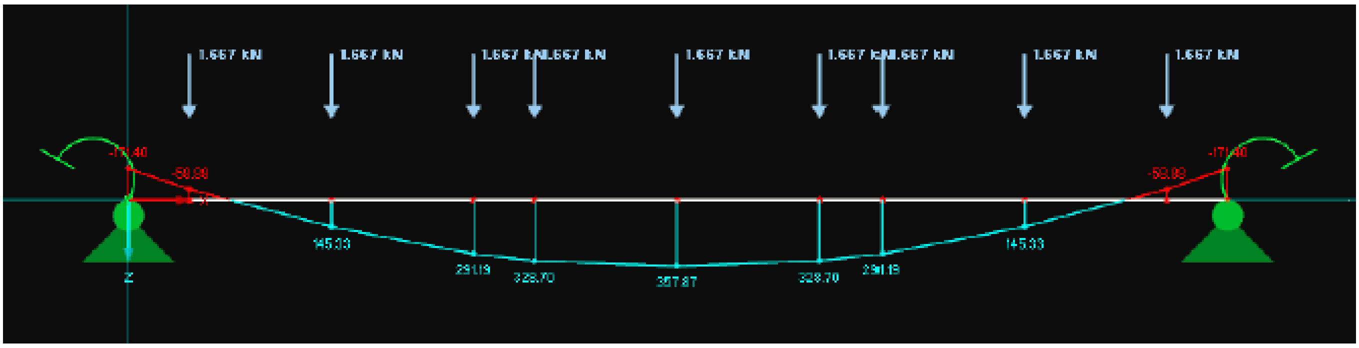


μ_{ln} = 7,313 kg $\quad$ μ = 1503,48 kg

σ_{ln} = 0,0712 $\quad$ σ = 107,18 kg

V = 0,07

Factors for obtaining the bending moment at the pallet beam from the compartment load using 10 kN pallets:



358 kNcm / 10 kN = 35,8 cm

171 kNcm / 10 kN = 17,1 cm

Standard deviation of the bending moment at mid span:

$\sigma_{E,beam}$ = 1,07 kN · 35,8 cm = 38 kNcm

Standard deviation of the bending moment at the rotational springs:

$\sigma_{E,BEC}$ = 1,07 kN · 17,1 cm = 18 kNcm

B) Standard deviation of the resistance side

Standard deviation of the bending capacity from literature [Oliver Kraus – Systemzuverlässigkeit...]:

Parameter Log-Normalverteilung	Momente
$\mu_{\ln,r} = 0{,}193 + \ln(M_{pl,y,Rk})$	$\mu_r = 1{,}21 \cdot M_{pl,y,Rk}$
$\sigma_{\ln,r} = 0{,}076$	$\sigma_r^2 = (0{,}092 \cdot M_{pl,y,Rk})^2$

Specified beam capacity: M_{Rk} = 696 kNcm

$\sigma_{R,beam}$ = 0,092 · 696 kNcm = 64 kNcm

Standard deviation of the bending capacity of the beam end connector (rotational spring) from testing (test report SSI Schäfer):

$\sigma_{R,BEC}$ = 5 kNcm

C) Comparison of the standard deviations σ_E and σ_R

Bending at mid span:

$\sigma_{E,beam}$ / $\sigma_{R,beam}$ = 38 kNcm / 64 kNcm = 0,59 > 0,16 OK

Bending at beam end connector:

$\sigma_{E,BEC}$ / $\sigma_{R,BEC}$ = 18 kNcm / 5 kNcm = 3,60 < 7,6 OK

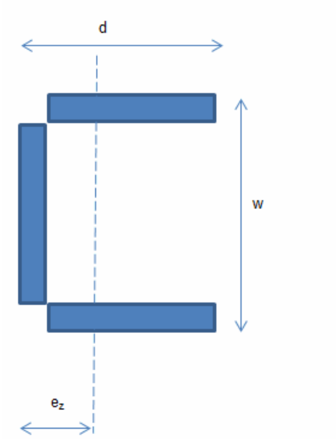
Conclusion:

The requirement 0,16 < σ_E/σ_R < 7,6 given in EN 1990 (equation C.7) for assuming the weighting factor α_E = -0,7 is fulfilled.

Annex D **Eccentricities**

D.1 General

The EN 15512:2009 allows neglecting bending moments due to eccentricities in joints when the relevant requirements of Figure D.2 and Figure D.5 are fulfilled. In order to estimate the influence of the eccentricities the upright sections properties are estimated for a simple U-profile (see Figure D.1).



e_z (mm)		t (mm)			
		1.5	2	3	5
d= w (mm)	80	27	27	27	27
	100	33	33	33	33
	120	40	40	40	40
	140	47	47	47	47

A (mm^2)		t (mm)			
		1.5	2	3	5
d= w (mm)	80	360	480	720	1200
	100	450	600	900	1500
	120	540	720	1080	1800
	140	630	840	1260	2100

I (mm^4)		t (mm)			
		1.5	2	3	5
d= w (mm)	80	170667	227556	341333	568889
	100	333333	444444	666667	1111111
	120	576000	768000	1152000	1920000
	140	914667	1219556	1829333	3048889

W (mm^3)		t (mm)			
		1.5	2	3	5
d= w (mm)	80	3200	4267	6400	10667
	100	5000	6667	10000	16667
	120	7200	9600	14400	24000
	140	9800	13067	19600	32667

0

Figure D.1— Estimated section properties

Four types are selected (see Table 31) to estimate the influence of the eccentricities.

Table 31 – Section of uprights

Type	w	d	t	A	I	w_z	e_z
	mm	mm	mm	mm²	mm²	mm²	mm
80.80.15	80	80	1.5	360	170667	3200	27
100.100.20	100	100	2	600	444444	6667	33
120.120.30	120	120	3	1080	1152000	14400	40
140x140.50	140	140	5	2100	3048889	32667	47

D.2 Bracing eccentricities

The following clause is part of EN 15512:2009;

8.6 Bracing eccentricities

If the eccentricities between system lines exceed the limits specified below, they shall be included in the global analysis and the resulting secondary moments shall be included in the member design.

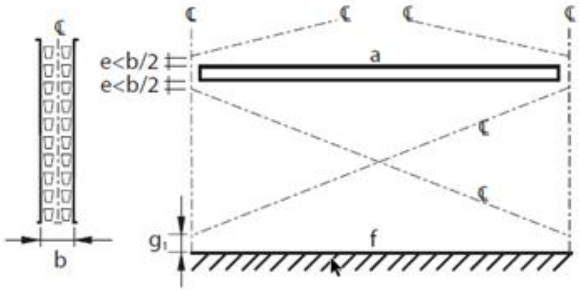
The effects of bracing eccentricities may be neglected if the following conditions are fulfilled.

a) The intersection point of the centre lines of a horizontal member and a diagonal falls within a vertical dimension 'e' equal to one half of the upright width 'b' (see Figure 11 a)).

b) The eccentricity 'g_1' is not greater than 2,0 times the upright width and 'g_2' is not greater than 1,5 times the upright depth as shown in Figure 11 b). Where beams are used as horizontal members, the intersection point shall be taken as the intersection of the centre lines of a diagonal and the top or bottom flange line.

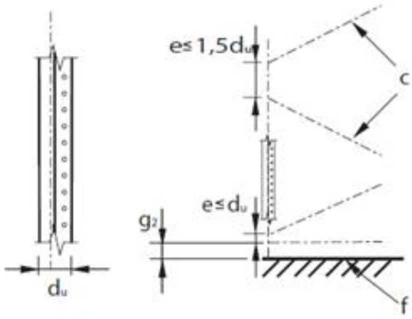
NOTE 1 It is good practice for the angle of inclination of the diagonal from the horizontal to lie between 20 ° and 70 °.

NOTE 2 If 8.6 requires a global analysis including eccentricities in the cross aisle direction, the bases shall be considered to be pinned unless the base stiffness is determined by test according to A.2.7



Key
- a pallet beam
- b width of upright
- c system lines
- e distance from bracing node to top or bottom of beam
- f floor
- g_1 distance from floor to lower spine bracing node point

Figure 11 a) — Eccentricities in spine bracing



Key
- c system lines
- d_u depth of upright
- e eccentricity between bracings
- f floor
- g_2 distance from floor to lower bracing node point

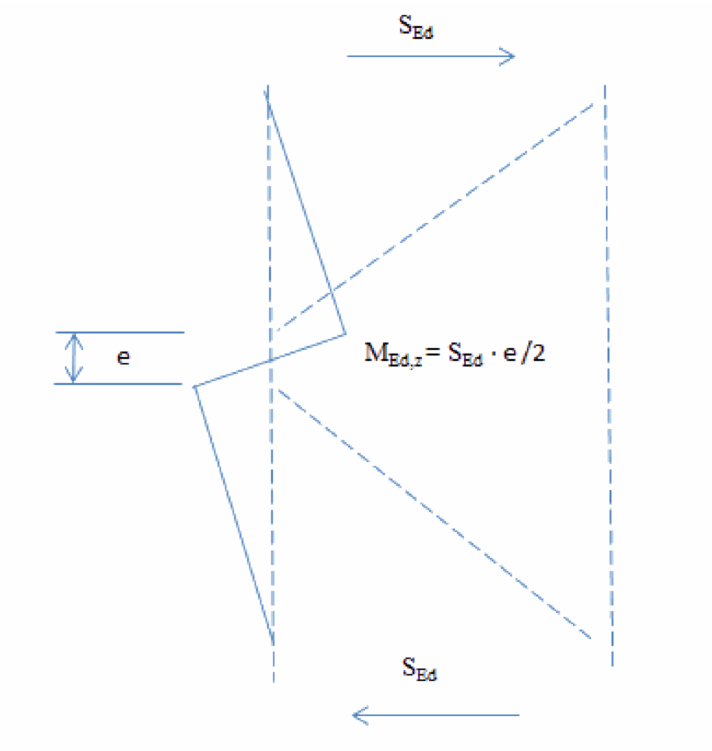
Figure 11 b) — Eccentricities in frame bracing

Figure D.2— Clause 8.6 of EN 15512:2009

Applying these rules to Table 31 leads to Table 32;

Table 32 – Allowed eccentricities

Type	d	$e_1 \leq$	$e_2 \leq$	$g_2 \leq$
	mm	mm	mm	mm
80.80.15	80	80	120	80
100.100.20	100	100	150	100
120.120.30	120	120	180	120
140x140.50	140	140	210	140
$e_1 \leq d$	eccentricity bottom horizontal to first diagonal			
$e_2 \leq 1.5\ d$	eccentricity bottom horizontal to first diagonal			
$g_2 \leq 1.5\ d$	eccentricity floor slab to first horizontal			



Key

S_{Ed} design shear force in frame

$M_{Ed,z}$ maximum bending moment in upright

e eccentricity between bracings

Figure D.3— Bending moment due to eccentricity e

Conversion of the bending moment $M_{Ed,z}$ to a normal force N^*:

$$N^* = \beta \frac{M_{Ed,z} \cdot A}{W_z}$$

where

β=0.6 stress contribution factor

$M_{Ed,z}$ bending moment in frame over weak axis

W_z section modulus of upright

A area of upright

Table 33 – Estimated effect of eccentricities for bolted frames

Case	Upright	1.5 du	S_{Ed}	$M_{Ed,z}$	$M_{Ed,z}/W_z$	N*	N^*/N_{RD}
1	80.80.15	120	0.48	0.029	9.0	1.9	0.02
2	80.80.15	120	0.72	0.043	13.5	2.9	0.03
3	80.80.15	120	0.55	0.033	10.2	2.2	0.03
4	100.100.20	150	0.95	0.072	10.7	3.9	0.03
5	80.80.15	120	0.50	0.030	9.3	2.0	0.02
6	100.100.20	150	0.78	0.059	8.8	3.2	0.02
7	80.80.15	120	0.54	0.032	10.0	2.2	0.03
8	120.120.30	180	0.92	0.082	5.7	3.7	0.01
9	80.80.15	120	2.22	0.133	41.7	9.0	0.11
10	100.100.20	150	3.96	0.297	44.6	16.0	0.11
11	80.80.15	120	1.46	0.088	27.4	5.9	0.07
12	120.120.30	180	2.73	0.245	17.0	11.0	0.04
13	100.100.20	150	1.23	0.093	13.9	5.0	0.04
14	140.140.50	210	2.28	0.240	7.3	9.3	0.02
15	80.80.15	120	2.22	0.133	41.7	9.0	0.11
16	100.100.20	150	3.96	0.297	44.6	16.0	0.11
17	80.80.15	120	1.46	0.088	27.4	5.9	0.07
18	120.120.30	180	2.73	0.245	17.0	11.0	0.04
19	100.100.20	150	1.23	0.093	13.9	5.0	0.04
20	140.140.50	210	2.28	0.240	7.3	9.3	0.02

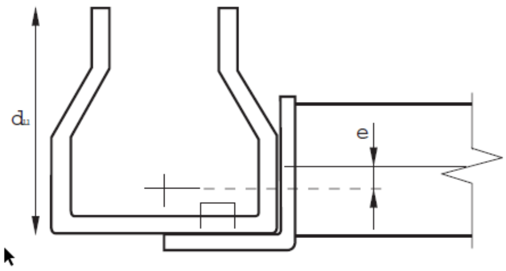
Table 33 shows that for most of the cases the effect is in the range of 2 to 4%. For cases with small uprights in automated racks (lateral crane load) the effect can be significant (11%). In practical applications these large eccentricities will hardly occur, but large shear forces are possible (high crane loads, wind load and seismic loads).

D.3 Eccentricities between beams and uprights

The following clause is part of EN 15512:2009;

8.7 Eccentricities between beams and uprights

The centroidal axis of the beam may not coincide with the centroidal axis of the upright. This results in an eccentricity 'e' in the cross-aisle direction as shown in Figure 12.



Key

d_u depth of upright

e eccentricity

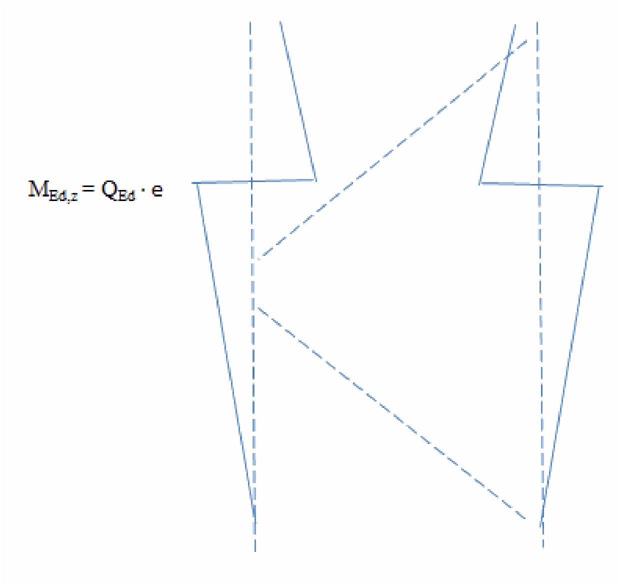
Figure 12 — Eccentricity in the cross-aisle direction

The eccentricity e in Figure 12 may be neglected where 'e' is less than 0,25 d_u.

NOTE This eccentricity e in Figure 12 may be important and should be included in both the global analysis and the member design if, for example, the beams are connected to the outside of the upright frames.

Figure D.4— Clause 8.7 of EN 15512:2009

The moment (M_z) induced by this eccentricity is shown in Figure D.5.



Key

Q_{Ed} design compartment load

$M_{Ed,z}$ maximum bending moment in upright

e eccentricity between load application point on beam and center of gravity upright

Figure D.5— Bending moment due to eccentricity e

Table 34 – Estimated effect of eccentricities for bolted frames

Case	Upright		e_{max} =0.25 d_u	N^*/N_{RD}		e	N^*/N_{RD}
1	80.80.15		20	0.07		-3.3	0.01
2	80.80.15		20	**0.24**		-3.3	0.04
3	80.80.15		20	0.07		-3.3	0.01
4	100.100.20		25	**0.14**		3.3	0.02
5	80.80.15		20	0.07		-3.3	0.01
6	100.100.20		25	**0.14**		3.3	0.02
7	80.80.15		20	0.07		-3.3	0.01
8	120.120.30		30	0.08		10.0	0.03
9	80.80.15		20	0.07		-3.3	0.01
10	100.100.20		25	**0.14**		3.3	0.02
11	80.80.15		20	0.07		-3.3	0.01
12	120.120.30		30	0.08		10.0	0.03
13	100.100.20		25	0.04		3.3	0.01
14	140.140.50		35	0.04		16.7	0.02
15	80.80.15		20	0.07		-3.3	0.01
16	100.100.20		25	**0.14**		3.3	0.02
17	80.80.15		20	0.07		-3.3	0.01
18	120.120.30		30	0.08		10.0	0.03
19	100.100.20		25	0.04		3.3	0.01
20	140.140.50		35	0.04		16.7	0.02

The two rights columns of Table 34 show that when the actual eccentricities of Table 31 are used, the effect is in the range of 1 to 4%. When the allowed eccentricities are used (e_{max}), the effect for case 2 is estimated to be 24%. Case 2 represents a very light upright in combination with a high compartment load and the maximum allowed eccentricity (0.25 d_u).

Bibliography

[1] C. 176, “EN1990 - basis of structural design,” 2013-03-15.

[2] JCSS, “Probabilistic model code, part 3: resistance models. joint committee on structural safety. published online at: http://www.jcss.byg.dtu.dk/,” 2001.

[3] Dr. O. Kraus, “CEN-TC344-WG1_N0081_BG_AW_Meeting_notes_Reliability_CEN_WG1.pdf” 31 May 2016.

[4] J. B. Schleich, G. Sedlacek, O. Kraus ”Realistic Safety Approach for Steel Structures Exposed to Extreme Wind and Snow Loading”, Proceedings of Eurosteel 2002, Coimbra, Portugal, 2002, p. 1521-1530

[5] T. Vrouwenvelder “EN 1990 – Basis of Structural Design – Annex B Reliability Differentiation, Annex C Reliability Theory”, Presentation for Workshop “Eurocodes – Background and Applications”, 18-20 February 2008, Brussels (Organised by the European Commission) https://eurocodes.jrc.ec.europa.eu/doc/WS2008/EN1990_5_Vrouwenvelder.pdf

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