Combination of Permanent and Variable Load Is Dependent

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Citation: Poutanen, T.; Pursiainen, S.; Länsivaara, T. Combination of Permanent and Variable Load Is Dependent. Appl. Sci. 2021, 11, 4434. https://doi.org/10.3390/app11104434

Abstract: This study concerns the combination of the permanent and the variable loads in the structural design. The Eurocodes are used as a reference. Three new findings are presented: (1) In each physical structure, and in every load pair of the permanent load and the variable load, the maximum variable load is the service time load, the 50-year load, i.e., the high value of the variable load. Therefore, no load reduction should be applied in the combination. (2) The governing hypothesis is the independent load combination (ILC) with random load pairs and random single loads. However, the load pairs are not independent as normally one variable load occurs simultaneously in multiple structures and in multiple load pairs inducing correlation between the loads, ultimately full correlation, and the dependent load combination (DLC). (3) In the current Eurocodes, the design load combination applies to one load pair only. However, one design load combination virtually always applies to multiple load pairs which demands using the DLC. The authors have explained earlier that the permanent and variable loads should be combined dependently as the ILC contradicts the physics. The new findings support this conclusion. Changing the current codes towards the DLC approach would simplify them and eases their use in the structural design work.

Keywords: load combination; structural design; code

1. Introduction

1.1. Limitations and Terms

This article addresses the combination of permanent and variable loads only. The Eurocodes and corresponding steel, timber and concrete codes are used as references [1–4] and terms of these codes apply.

Some further terms are cleared up:

Design load combination. The load combination which is made in the structural design from the deterministic load table values of permanent and variable loads. The design load combination can be made in three alternative ways, independently, dependently, and semi-dependently. The semi-dependent combination is omitted here as it is not applied in any codes.

1. Independent load combination, ILC. This load combination is realized by the ILC model where the combination load is constructed from single and random load pairs omitting load groups including a random permanent load and a random variable load. The probability of simultaneous occurrence of the high values of the loads is low and therefore a load reduction of approximately 10% is applied regarding the arithmetic sum of actual load table values. The load reduction is normally implemented by two safety factors of the permanent load, in the Eurocodes, $\gamma_G = 1.15$ and $1.35$. In the Monte-Carlo (MC) analysis a random seed number is selected for the permanent
load and for the variable load, the loads are computed from the distributions and the combination load is the arithmetic sum of these loads. The same result is obtained by using the convolution equation. The ILC is never applied in the serviceability state (SLS) while it is normally applied in the ultimate limit state (ULS). According to the governing hypotheses, it should always be applied in the ULS. However, it is not always applied, as in the combination rule (8.12) of the Eurocodes. Due to the load reduction, the ILC is in contradiction with physics and deterministic mechanics [5].

2. Dependent load combination DLC. The combination load is constructed as if the distributions were correlated. In the MC analysis one random seed number is selected, the same used for the permanent load and for the variable load, the loads are computed from the distributions and the combination load is the arithmetic sum of the loads. That is, the combination load distribution is obtained by adding up the partial loads by fractiles. The convolution equation can also be used given with a constraint that the combination load distribution crosses the crossing point of the partial distributions [6]. In the DLC no load reduction appears. The combination load is the arithmetic sum of the partial loads, i.e., the design load is obtained by adding up the load table values normally multiplied by load factors. The DLC matches with the physics and deterministic mechanics [5]. The DLC is always applied in the SLS and sometimes in the ULS.

**Physical load combination.** The load combination in the actual structure by the permanent and the variable load. The combination is deterministic and follows the rules of structural mechanics. These loads are scattered in time and space and are modelled by statistics. The physical load combination has three characteristics.

1. The service time variable load always strikes every actual structure and every permanent load—variable load combination. In other words, in this load combination the maximum variable load is always the same, the 50-year load, not the 5-year load assumed currently. The combination is made between a random permanent load and a fixed variable load. In the actual design the variable load is given a constant table-based value and the combination means adding a constant to the random permanent load, such combination is deterministic. If we assume that the 50-year variable load is random the combination is also deterministic or almost deterministic as the variable load simultaneously strikes multiple permanent loads. Thus, a load reduction cannot be made.

2. One design load combination, i.e., one design, simultaneously applies to multiple structures and multiple physical load combinations, and the design load combination should be valid in all these physical load combinations. Currently, one design load combination is valid for one physical load combination only.

3. The current assumption is that the physical load pairs are independent; however, they are not as adjacent load pairs often have the same variable load.

**Design criterion.** Structural codes define target reliability, i.e., the maximum probability for a failure. There are two options to define this criterion:

1. In the governing hypotheses the target reliability applies to one physical load pair. This definition allows the interlacing of high load values and the load reduction. This definition omits the following points
   - The variable load is always the 50-year load;
   - There are often multiple adjacent load pairs with the same variable load; and
   - One design load combination often applies to multiple structures and multiple physical load combinations.

2. A modified design criterion is proposed here:
   - The design criterion applies to the load combination in the design. If this load combination applies to multiple physical load combinations, the criterion must be valid in all these physical load pairs. The variable load in all design load pairs and in all physical load pairs is the 50-year load.
1.2. Review

A comprehensive review on load combination has been given recently in [7]. The current hypotheses for the combination of the permanent and the variable load is based on random load pairs with random single loads, the ILC and load reduction [1,7–15].

The structural codes and articles regarding codes are divided into three accuracy levels: I, II, and III. The Eurocodes [1] were earlier based on level I, i.e., on deterministic, historic, and empiric methods.

The safety factors of the current Eurocodes are based on level II, i.e., on the first order reliability method. The primary assumption of this method is the independent load combination where a load reduction occurs. It is implemented by sensitivity factors $\alpha_E$ and $\alpha_R$, which decrease the target reliability and cause the load reduction as in this load combination it is improbable that the highest permanent and variable load occur simultaneously.

The accuracy level III is a full probabilistic method which is not applied in any codes so far.

In the current codes, the load combination is ambiguous:

1. In the ULS design, the permanent and the variable loads are often combined under the assumption that the loads are statistically independent, and the ILC is applied although this is not consistent throughout the codes [1]. However, the DLC is always applied in the SLS design. In the ULS the loads are high and therefore a load reduction is applied in the ILC. In the SLS the loads are low and the theory of the ILC correspondingly demands a load increase but it is not applied.

2. Permanent loads are independent with each other in the same way as the permanent and variable loads which suggests the ILC. However, the DLC is always applied.

Thus, one can argue that the codes do not always treat the load combination consistently. This article suggests that permanent and variable loads should be combined dependently, an approach which would remove any ambiguity related to choosing the combination of these loads.

1.3. The Target of the Article

The governing hypothesis for the combination of the permanent and the variable load is the ILC. In the Eurocodes both the ILC and the DLC are applied, i.e., the combination is unclear. The target of this article is to show that the DLC should be applied as the ILC leads to unsafe design regarding the target reliability.

2. Materials and Methods

Equations are given which can be used to calculate load combinations of single loads and load groups using various assumptions [5,6,16].

The uncertainty is omitted.

The target reliability index is $\beta_{50} = 3.83$, i.e., the 50-year failure probability is $P_{50} = 1/15000$. The design point is fixed to unity, where the characteristic values of the distributions are fixed, i.e., to the mean of the permanent load distribution, the 50-year return load of the variable load distribution and the 0.05 fractile of the material property distribution.

The permanent load distribution $G(x; \mu_G, \sigma_G)$ is normal $G(x; 1, 0.091)$, $V_G = 0.091$, $\gamma_G = 1.35$.

The variable load distribution $Q(x; \mu_Q, \sigma_Q)$ is the 50-year return load given by Gumbel distribution $G(x; 0.491, 0.196)$, $V_Q = 0.4$, $\gamma_Q = 1.5$.

The loads are combined with load proportion $\alpha$, the variable load in the total load, $\alpha = \mu_Q/\mu_G + \mu_Q$.

Safety factors are calculated for timber material [4] using various load combination options. The distribution is assumed log-normal, 0.05 fractile fixed to the design point, $M(x; 1.412, 0.282)$, $V_M = 0.2$. 
When one load \( L \) with the cumulative distribution \( F_L(x; \mu_L, \sigma_L) \) and the safety factor \( \gamma_L \) strikes a material with the density distribution of \( f_M(x; \mu_M, \sigma_M) \), the equation to calculate the safety factors \( \gamma_L \) or \( \gamma_M \) or the failure probability \( P_f \) is

\[
\int_0^\infty F_L(x; \gamma_L) f_M(x; \gamma_M) \, dx = 1 - P_f.
\]

Both distributions are fixed with equal characteristic values.

The cumulative distribution of the ILC is calculated by using the convolution equation \([5,6,16]\),

\[
F_i = \int_{-\infty}^{\infty} G\left( r; \frac{\mu_G(1-\alpha)}{\gamma_G}, \frac{\sigma_G(1-\alpha)}{\gamma_G} \right)^n \frac{d}{dx} Q\left( x - r; \frac{\mu_Q \alpha}{\gamma_Q}, \frac{\sigma_Q \alpha}{\gamma_Q} \right)^m \, dr,
\]

where \( G \) and \( Q \) are the cumulative distributions of the permanent and the variable load, \( n \) is the number of the permanent loads in the combination, \( m \) is the number of years for which the calculation is made.

The dependent load combination is obtained by adding up the distributions by fractiles or more simply the cumulative distribution of the DLC is obtained by using recursive equation \([5,6,16]\)

\[
F_d = \left\lfloor \frac{y}{\gamma_G} \right\rfloor G\left( x - r; \frac{\mu_G(1-\alpha)}{\gamma_G}, \frac{\sigma_G(1-\alpha)}{\gamma_G} \right)^n - Q\left( x - r; \frac{\mu_Q \alpha}{\gamma_Q}, \frac{\sigma_Q \alpha}{\gamma_Q} \right)^m, \right. \]

\[
F_d = Q\left( y; \frac{\mu_Q \alpha}{\gamma_Q}, \frac{\sigma_Q \alpha}{\gamma_Q} \right)^m.
\]

3. Results

We present the following five arguments to justify that the permanent load and the variable load should be combined dependently:

1. The ILC contradicts the physics, see Section 3.1.
2. The load combination is a combination of a random permanent load and a fixed 50-year variable load. The interlacing of the high values of the loads does not occur as the variable load is always the high value and the load reduction cannot be applied.
3. One variable load often occurs simultaneously with multiple structures and multiple permanent loads which induces correlation between the loads, ultimately full correlation.
4. One design load combination simultaneously applies to multiple structures and physical load combinations, the design load combination must be valid in all these physical load combinations, the ILC is thus unsafe.
5. One variable load often occurs simultaneously in multiple permanent loads, i.e., the load pairs are not random. The basic assumption of the ILC, i.e., random load pairs with random single loads is thus wrong.

Arguments 1 and 2 demand full dependency and correlation in the combination. Arguments 3 and 4 disclose that the combination is sometimes fully or at least almost fully dependent in cases when one variable load simultaneously strikes multiple permanent loads. Argument 5 reveals that the basic assumption of the ILC is wrong.

3.1. The ILC Contradicts the Physics

Figure 1 has been obtained applying the factored cumulative distributions of the Eurocodes. The cumulative distribution of the permanent load is shown by the solid line and the corresponding 50-year variable load distribution by the dashed line. These distributions are the design load distributions and they in this case apply to one physical load pair only according to the current design. The dash-dotted line denotes the DLC (3) and the dotted line the ILC (2), the load ratio is \( \alpha = 0.5 \). The distribution of the DLC crosses the crossing point of partial distributions, but the distribution of the ILC does not. In the load of the crossing point 0.779, the load halves correspond to equal effect in the actual
structure with the same occurrence probability. We know from physics that the sum of these halves is the same as each full load. This can be proved in the reality: One half of the structure is constructed and loaded by the permanent load. The other half is added and loaded with the variable load. The resistance of the total structure is the arithmetic sum of the halves [5]. The ILC does not fulfil this condition and is in contradiction with the physics and deterministic mechanic. The contradiction applies to all load proportions $\alpha$.

![Figure 1](image.png)

**Figure 1.** Cumulative load distributions as function of load. The permanent load, solid line; the variable load, dashed line; the DLC, dash-dotted line; the ILC, dotted line combined with 50% permanent load and 50% variable load, $\alpha = 0.5$. In this Figure unity denotes the mean permanent load and the 50-year return load of the variable load.

### 3.2. The Material Safety Factor of Timber

Figure 2 includes material safety factors of timber calculated using various methods:

The dash-dotted line denotes the currently applied approach, where the loads are combined independently, and the variable load distribution is in the 5-year mode (2). This is clearly wrong, as the 50-year variable load definitively strikes all structures and all load combinations.

The dotted line shows to the ILC where the variable load is in the 50-year mode (2). The solid line depicts the DLC (3).

In the structural design the variable load is constant. Dashed line means a calculation where the variable load has a constant value which is added to the permanent load distribution. The calculation is made by using the DLC and assuming the coefficient of variability of the variable load is 0.05. We find that this calculation results in 0–2.5% higher safety factor than the DLC.

All calculations lead to the same result in the case of the permanent load. The current approach (dash-dotted line) results in about 20% lower safety factor than other alternatives when the variable load is dominant. The dotted line, i.e., the ILC with 50-year variable load is 0–6% lower than the DLC. In this calculation the group effect is not considered and if taken into account, the line will be closer to the DLC.
Figure 2. Material safety factors of timber; dash-dotted line, current calculation, the variable load is in the 5-year mode; dotted line, the ILC with the variable load in the 50-year mode; solid line, the DLC; dashed line, the variable load is assumed constant.

3.3. Load Groups

Assume that a roof has n similar girders spaced equally apart from each other, designed for 50 years in one process, i.e., one design and one design load combination apply to all girders. Each girder i has different permanent load \( g_i \), which is the self-weight of the girder plus the weight of the roof structure in the area of the girder length by the spacing. One of the n girders has the maximum permanent load \( g_{\text{max}} \).

In this case, the variable load is assumed to be a layer of snow uniformly distributed over the roof, as assumed in the codes and as is typically the case in the reality.

Each year j of the service time has different variable load \( q_{j,i} \) affecting girder i which is the actual snow load multiplied by the impact area of the girder i. The maximum snow load \( q_{\text{max}} \) occurs one year j into the service life. This load \( q_{\text{max}} \) occurs simultaneously with all the girders of the roof, including the one with the maximum permanent load \( g_{\text{max}} \). Consequently, the maximum loads \( g_{\text{max}} \) and \( q_{\text{max}} \) are simultaneous and the maximum combination load is \( gq_{\text{max}} = g_{\text{max}} + q_{\text{max}} \). An analogous reasoning shows that the next greatest loads \( g_{\text{max}-1} \) and \( q_{\text{max}-1} \) are also simultaneous and the second largest combination load is \( gq_{\text{max}-1} = g_{\text{max}-1} + q_{\text{max}-1} \) Thus, full correlation exists between the loads in the combination although any single pair of G and Q is independent.

The assumption of the independent load combination wrongly results in that the probability for the maximum loads \( g_{\text{max}} \) and \( q_{\text{max}} \) to occur simultaneously is only 1/50 but is 1.

The example above shows that maximum variable load \( q_{\text{max}} \) and the maximum permanent load \( g_{\text{max}} \) are simultaneous which suggest the DLC.

This example shows that the 50-year loads strike every structure. That is, the load combination is not made between random load pairs but rather between a random permanent load and the fixed 50-year variable load.

The ILC is based on combination of single load pairs of one permanent load and one variable load, i.e., one permanent load is randomly picked and combined with a random variable load, and one may argue that the reasoning above concerning the group effect is
irrelevant. However, although the loads are combined by single load pairs the DLC should be used as the permanent load distribution and the variable load distributions are fully correlated in the combination in this case. Further, the basic assumption of the ILC is that adjacent load pairs are independent. Consequently, this example shows that the adjacent load pairs are not independent, even though, the permanent loads in the adjacent load pairs are independent but the variable loads are not.

3.4. A Large Load Group

Assume that a detached housing estate comprises 100 houses with trussed roofs and there are similar 10 trusses in all houses based on one design and one design combination load. One may assume that one truss has 15 failure sources. Thus, the estate has a total of 15,000 failure sources and physical load combinations on the roofs. Assume further that the total area of the estate is 1 km$^2$, i.e., one hectare per house, as such communities are common in Europe where the Eurocodes are applied. It is reasonable to assume that the climatic loads, e.g., wind and snow, are the same for the whole estate over such a small area. Consequently, the variable loads have a similar effect on all the houses and their failure sources and the load combinations. As with the roof girder example explained above, there is a full correlation between the permanent load and the variable load and, therefore, DLC must be applied.

A critical issue is what is the failure probability of the roofs of this community. If the loads are combined independently and the structural design is made according to the current Eurocodes the failure probability of each failure source $P_{f10} = 1/15000$. However, the simultaneous variable loads over all roofs make the combination dependent as explained in next section. Interlacing of high permanent loads and high variable loads does not occur and the failure probability is about ten times higher $P_{f50} = 1/1500$. This example shows that the group effect alone is sufficient to show that the load should be combined dependently.

3.5. Numerical Exercise

In Figures 3 and 4, the load combination for the full 50-year variable load and group of full permanent loads is given, $m = 50$, i.e., one 50-year variable load simultaneously occurs with $n = 1, 50, 500$, and 5000 permanent loads: thin solid line, dashed line, dash-dotted line, and dotted line, respectively. Thick solid line applies to the DLC of the 50-year variable load and one permanent load. The horizontal dashed line means the target reliability $\beta_{50} = 3.83$, i.e., 0.99993496.

The independent loads at the target reliability are $n = 1, 1.208; n = 50, 1.275; n = 500, 1.302; n = 5000, 1.323$, and the dependent load is 1.326. The independent combinations result in a load reduction of 9%, 4%, 2%, and 0% with respect to the dependent combination.

The calculation is made above for load proportion 50%. A considerable load reduction in the ILC regarding the DLC occurs in load proportions between 20 and 80%, which is common in the structural design.

One design load combination may apply to multiple structures and physical load combinations with the same variable load. The calculation above shows when the number of the multiple structures and physical load pairs increases the combination approaches the DLC.
4. Discussion

The basic assumption of the ILC is that the combination load is constructed from independent and uncorrelated load pairs of permanent and variable loads. However, the loads are correlated as the ILC contradicts the physics and should be combined dependently as explained in Section 3.1. The physics demand that the loads must be combined as if the loads have a full correlation.

The current hypothesis is, that the variable load in the structural design is random. However, the maximum variable load is the 50-year load as this load strikes all structures and all load combinations, i.e., this load is not random, and the load reduction is not acceptable. The current calculation applies a load reduction to this load and erroneously uses the 5-year load in the load combination. When the 50-year variable load and the random permanent load is combined independently the result is almost the same as the DLC and only 0–6% lower as
seen in Figure 2. This combination will be even closer to the DLC when the group effect is considered. If the load group is 50 with the same variable load and multiple permanent loads about one half of the load reduction is removed as disclosed in Section 3.5.

It is feasible to assume that the 50-year variable load is constant and that is combined with the random permanent load. Such assumption almost fully equals the DLC as seen in Figure 2.

One variable load occurring simultaneously with multiple permanent loads induces correlation and load increase regarding the ILC. It is possible that the load group includes 5000 permanent loads meaning that no load reduction can be applied as explained in Section 3.5.

It is also feasible to set the design criterion in such a way that the criterion must be fulfilled in all cases the design applies to, which would demand the DLC for load groups with the same variable load.

Finally, the basic assumption of the ILC is incorrect. Namely, the load pairs are not independent as the variable load may be the same in adjacent load pairs.

The motivation for using the ILC is that it reduces the design loads and the material costs. However, compared with the DLC approach, the ILC leads some amount of to load vanishing in the combination process and the failure probability exceeds, thus, the target reliability as laid down in the codes. As suggested by the numerical evaluation of this study, a total of 0–20% of the load can vanish in the ILC process, meaning that the failure probability is about ten times that of the DLC approach. The intended target reliability of the Eurocodes is $\beta_{50} = 3.8$, but the ILC can result in a reliability value as low as about $\beta_{50} = 3.2$.

In the current codes, the ILC is normally implemented by two permanent load factors greater than unity. However, the correct load combination may include only one permanent load factor greater than unity. The Eurocodes include three combination rules. One of these (8.12), i.e., $1.35G + 1.5Q$ utilizes the DLC and the other two (8.13a,b), $\max(1.15G + 1.5Q, 1.35G + 1.05Q)$ and (8.14a,b), $\max(1.35G, 1.15G + 1.5Q)$ correspond to the ILC. The combination rule (8.12) of the Eurocodes is correct, but the safety factors and the failure probability are calculated erroneously. Namely the variable loads are calculated for five-year loads only [16] whereas they should be calculated for 50-year loads. The current Eurocodes in unclear regarding the load combination as both the ILC and the DLC are applied.

The present calculation suggests that the variable load safety factor $\gamma_Q = 1.5$ of the Eurocodes should be increased by about 20% if the target reliability is kept unchanged, $\beta_{50} = 3.83$. A feasible solution is that the target reliability is lowered to about $\beta_{50} = 3.2$ when the reliability calculation for timber and concrete approximately remains unchanged but the material safety factor of steel $\gamma_M = 1.0$ should be increased considerably. The authors also suggest that the load distribution of the variable load should be changed from Gumbel to modified Gumbel [17] where the upper tail of the distribution is removed which would mitigate the changes.

The authors implemented dependent and independent load combination for test loading. The DLC results in simpler calculation with more sable results [18].

We emphasize that the ILC principle also necessitates some extra work in the structural design, since multiple load safety factors are needed. Using the DLC is thereby justified also in terms of the ease of design.

Finally, based on the above arguments, we conclude that using the DLC principle in a systematic way would reduce the inconsistencies and contradictions related to the load combination procedure as it is currently presented in both the codes and in structural probability theory.

5. Conclusions

The permanent and variable load should be combined dependently in the structural design to achieve reliable outcomes and structural safety. The independent load combination (ILC) used in the Eurocodes (8.13a,b) and (8.14a,b) leads to unsafe design with respect
to the target reliability, while the dependent combination (DLC) (8.12) can be interpreted as the correct approach. Nevertheless, the safety factor and the reliability calculation are currently based on the ILC instead of the DLC. We propose that adopting the DLC principle as a standard way of combining loads will simplify the codes and the design work and eliminate the inconsistencies related to the load combination in the current codes.

**Author Contributions:** Conceptualization, T.P. and T.L.; methodology, T.P.; software, T.P.; validation, T.P. and S.P.; formal analysis, T.P.; investigation, T.P.; data curation, T.P.; writing—original draft preparation, T.P. and S.P.; writing—review and editing, S.P., and T.L.; visualization, T.P. and S.P.; supervision, T.L.; project administration, T.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable. (This study is completely based on mathematical and numerical modelling. It does not involve any use of humans or animals.)

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data is contained within the article. The data presented in the figures of this study can all be reproduced using the equations given in the study.

**Conflicts of Interest:** The authors declare no conflict of interest.

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