# Suggestions by the Preventing Methods for Bolt Failures, 10th (Final) Report

## Failure of Fastening Screws and Their Preventive Methods

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## Introduction

As described in 1st report, a large number of bolts have been used in a wide variety of machines and equipment, such as electrical equipment, machine tools, construction machinery, rolling-stock, steel towers, bridges, transportation equipment, etc. In addition, more than 90% of failure cases would be directly and indirectly caused by fatigue and fabricators would be responsible for 80% of failure cases.

According to the above results, several examples of bolt failure are described by fatigue and their macroscopic fracture surfaces are analyzed with simple calculation methods in the second report.

Environmental failures of bolts are introduced in the 3rd and 4th reports accompanying their countermeasures. These are corrosion fatigue, delayed fracture and SCC (stress corrosion crack). In addition, the factors related to the fatigue strength of bolts are analyzed and the conventional improvement methods for bolts are presented in the 5th report.

A new method for improvement of the fatigue strength of a bolt is introduced in the 6th report and 7th one. In the first half of the reports, the author has tried to analyze the effect of many factors related to the fatigue strength of bolts and nuts for a fundamental approach. Then, the four main factors, which control the fatigue strength of a bolt, have been clarified in the last half of the reports. The countermeasure against the above four factors is proposed for the purpose of fatigue strength improvement and this is called "CD bolt" as the brand name.

Some examples of practical applications of the CD bolts are presented in the 8th report.

In addition, loosening of bolts and its countermeasures have been exhibited in the 9th report, because they are closely related to the fatigue failures of bolts.

As this report is the final one, the author would like to present from the beginning of research to the fatigue strength of a bolt and some general suggestions through preventive methods for bolt failures.

## Starting Point for Research and Development of Bolts for Failures

### Starting to Research "Fatigue Prevention" of Bolts

The giant bolts, which had been used in the rolling mill and failed due to fatigue after just 3 years since start of the operation. The loss from the failure at that time was over 500 million yen. In addition, the effective method for fatigue strength improvement of a bolt had not been presented by referring to the past various kinds of the researching papers and the text books. **Figures 10.1** shows the schematic illustration of rolling mill and the position of failure (see the second report). Failure was detected in two out of four tie rods (giant bolts). One bolt was perfectly broken and the other one was partly cracked. **Figure 10.2** shows the outer appearance of the fracture surface of the giant bolt, which is called "tie rod". This giant bolt was broken from fatigue and this big failure accident becomes "the start of bolt research" for the author himself.

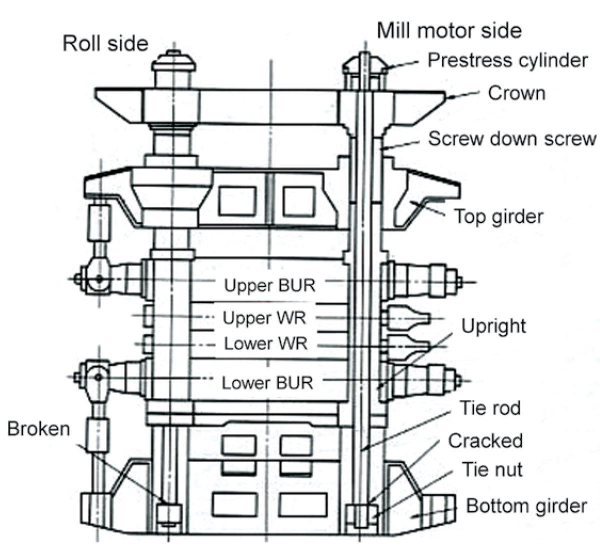



**Fig.10.1 Schematic illustration of rolling mill and position of failure**

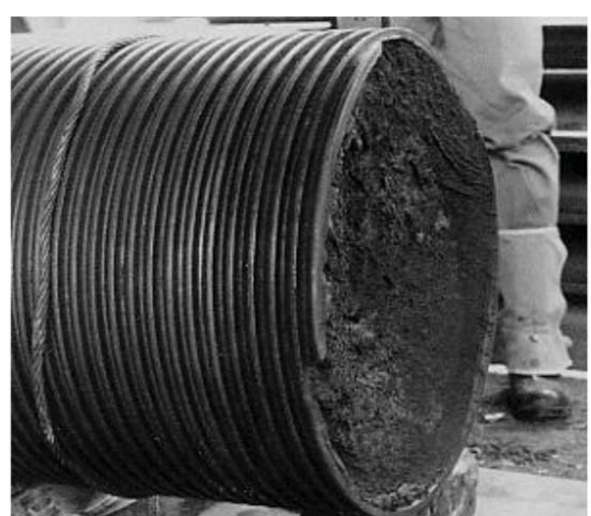


**Fig10.2 Outer appearance of fracture surface of the tie-rod**

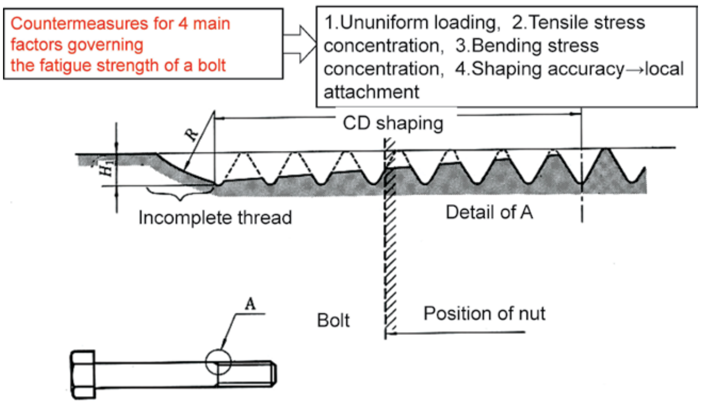



Fig.10.3 Typical shape of anti-fatigue bolt (CD bolt)

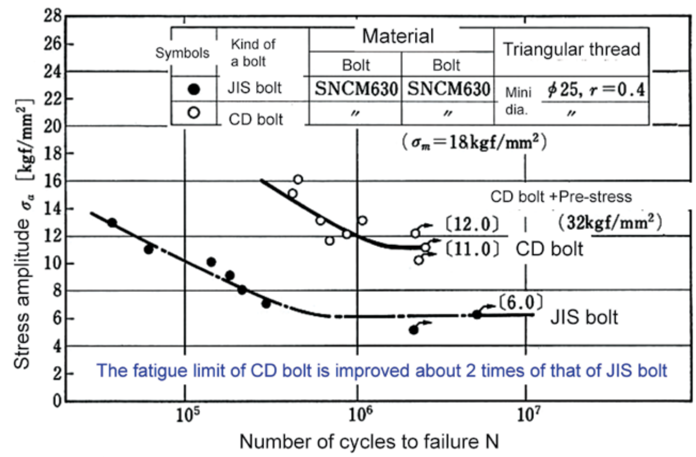



Fig. 10.4 S-N curve for CD bolt

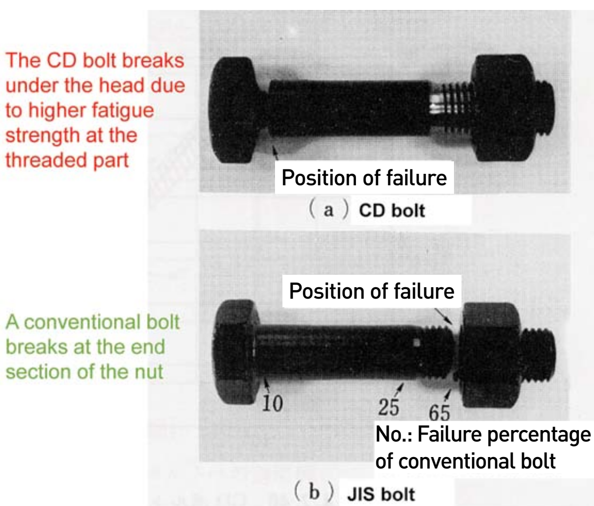



Fig. 10.5 Difference in position of failure between (a)CD bolt and (b)conventional bolt

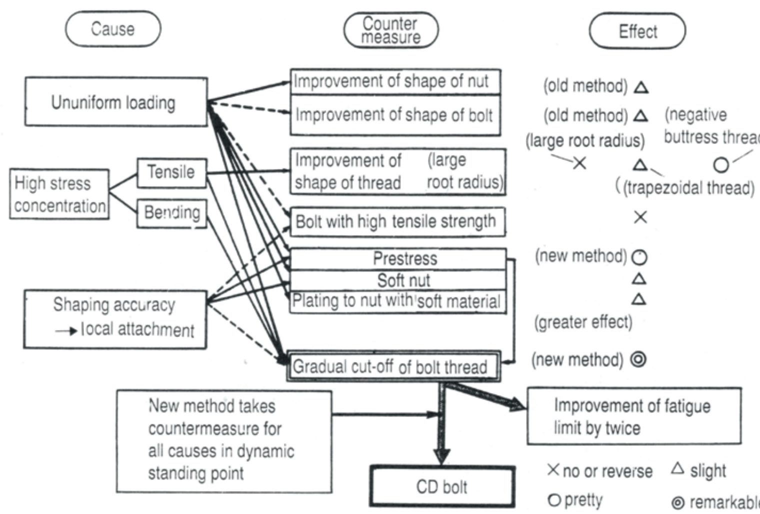



Fig.10.6 Four main factors governing the fatigue strength of bolts, countermeasures and their effects[2)]

## Development of "Anti-fatigue Bolt"

According to the above bolt failure, various kinds of tests on bolts have been performed as shown in the past reports (see 6th and 7th ones) and the following items have been clarified. That is, though there exist many factors related to the fatigue strength of bolts, those are hardly or slightly affected by the conventional factors, e.g. type of thread, root radius, bolt or nut materials, etc. The fatigue strength of a bolt was fairly increased by only pre-stressing and the ratios of increase in fatigue strength were 38 and 50%, respectively by comparing to a conventional one.

According to the results of the various kinds of the fatigue tests as shown above, the author had presented the new method for fatigue strength improvement of bolts. **Figure 10.3** shows the typical shape of the anti-fatigue bolt (the CD bolt).

**Table 10.1 Comparison between conventional bolt and CD one**

| | Conventional bolt | CD bolt |
|---|---|---|
| Ununiform loading | The load on the first thread becomes 1/3 in engagernent with nut thread. | The load on the first thread decreases to half of conventional one |
| Tensile stress concen-tration | High stress concentration | Decrease of stress concentration |
| Bending stress concen-tration | High stress concentration | Decrease of stress concentration |
| Local attachment | Remarkable in high tensile material and large diameter | Smaller contact area bolt thread in engagement with nut thread |

**Figure 10.4** shows S-N curve of the CD bolt and a conventional (JIS) one. Fatigue strength of the CD bolt (at 2x106 cycles); the fatigue limit of the CD bolt is nearly two times of that of the conventional bolt. This improvement is remarkable because a bolt is a kind of notched specimen and the load is transmitted by the contact between the threads of a bolt and a nut. In addition, **Fig.10.5** shows the difference in position of failure between the CD bolt and a conventional (JIS) one. As can be shown from this figure, the CD bolt was broken from the underhead fillet and a JIS bolt was from the end section of engagement to a nut. These results had verified that the CD bolt had taken the countermeasures against four main factors governing the fatigue strength of a bolt. The above results would be considered to be the first achievement in the world for the outstanding improvement of fatigue strength. The reason why the above results are induced is to eliminate or relax all of the factors governing the fatigue strength of bolts (Fig.10.6 and Table 10.1). That is, the CD shaping is designed so that all of these factors are eliminated only by taking the most appropriate measure as shown in **Fig. 10.6** and **Table 10.1**, respectively.

In this case, $F_t$ and $F_c$ are expressed as shown below:

$$F_t = K_t \cdot \lambda \qquad \cdots(1)$$

$$F_c = K_c \cdot \lambda \qquad \cdots(2)$$

From the balance of forces,

$$W_a = (F_f + F_t) - (F_f - F_c) = F_t + F_c \qquad \cdots(3)$$

Substituting eqs. (1) and (2) into Eq.(3)

$$W_a = (K_t + K_c) \cdot \lambda$$

$$\lambda = \frac{1}{K_t + K_c} W_a \qquad \cdots(4)$$

Substituting eq. (4) into eqs. (1) and (2)

$$F_t = \frac{K_t}{K_t + K_c} W_a \qquad F_c = \frac{K_c}{K_t + K_c} W_a \qquad \cdots(5)$$

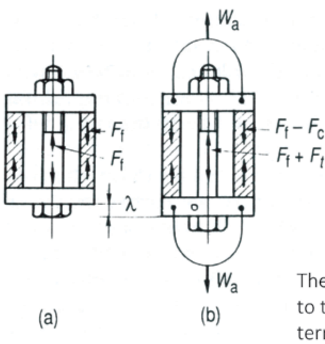



Fig. 10.7 Balancing relation between external force and internal forces applied to the screw-fastened member ($W_a$, external force; $F_f$, $F_t$, $F_c$, internal forces)

The ratio of the tensile force $K_t$ added to the bolt by the external force $W_a$ to the external force $W_a$ applied to the fastening screw is expressed in terms of the internal force coefficient ϕ of the bolt as shown below:

$$\phi = \frac{K_t}{W_a} = \frac{K_t}{K_t + K_c} \qquad \cdots(6)$$

$F_t$ and $F_c$ in eq. (5) can be expressed as shown below by using ϕ

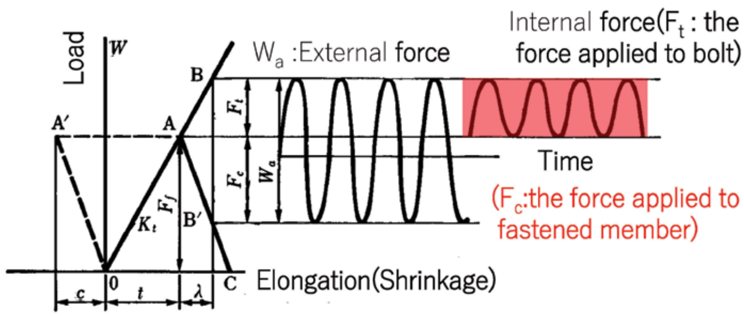
$$F_t = \phi W_a$$

$$F_c = (1 - \phi) W_a \qquad \cdots(7)$$

$K_t$: Spring constant of bolt

$K_c$: Spring constant of fastened member

$F_f$: Tightening force to bolt




$K_t$ :Spring constant of bolt, $K_c$ :Spring constant of fastened member,
$W_a$: External force less than tightening force, $F_f$ :Tightening force to bolt,
$F_t$ :Internal force due to external varying force $W_a$, $F_c$: ref. to the above

Internal force due to external force $W_a$ :
one fifth of external force in the case of Φ=0.2

$$F_t = \frac{K_t}{K_t + K_c} W_a \qquad \cdots\cdots\cdots(8)$$

Maximum force applied to bolt

$$F_{max} = F_f + \frac{K_t}{K_t + K_c} W_a \qquad \cdots\cdots\cdots(9)$$

**Fig. 10.8 Relation between the force and shrinkage in the bolt and fastened member**

**Figure 10.6** shows the four main factors governing the fatigue strength of bolts and countermeasures and their effects). In addition, **Table 10.1** lists the comparison between a conventional bolt and the CD one related to the four factors as shown in **Fig.10.6**. **The author had at first clarified the four main factors governing the fatigue strength of a bolt in the world. That is, (1)ununiform loading, (2)tensile stress concentration, (3)bending stress concentration and (4)shaping accuracy (local attachment) (see the 7th report).** It can be understood that only CD bolt takes countermeasures for these four factors.

## Development of "Anti-loosening of Bolts"

Though anti-fatigue of bolts is also very important for their performance, the anti-loosening screws could be also considered to be useful in view of balancing between external force and internal one applied to a screw-fastened member. **Figure 10.7** shows the importance of anti-loosening of the screws. In addition, **Fig.10.8** shows the relation between force and shrinkage in the bolt and the fastened member. According to the above Figs., the bolt is subject to only a small part of the external force, as far as the bolt is not loose (see the 9th report).

Though there are many kinds of anti-loosening fasteners or tools in the market, these are all expensive, heavy or are not suitable for reuse of fasteners, etc.

Anti-loosening properties are very important for their safety of the fastened portion as referred above, that is, to avoid from fatigue fracture following loosening. The author has considered that a small improvement will be enough for anti-loosening, because the tightened bolt has the property to be hard to loosen. Therefore, the following three kinds of anti-loosening measures have been presented; (1) First of all, the pitch difference between a bolt and a nut; **Figure 10.9** shows the enlargement of engaged portion between a bolt and a nut. As can be seen from this figure, the pitch of a bolt appears equal to the pitch of a nut from the both engagement. The pitch of a bolt is not necessarily put together to be the same pitch of a nut. When pn is the pitch of a nut and pb is that of a bolt, respectively, the condition, pn>pb and the difference of the both is settled to be small. Then, the axial force acts to widen the distance of screw thread according to engagement between a bolt and a nut and this force exhibits the anti-loosening property between the both. In addition, the compressive stress appears at the bottom of the thread of the most dangerous section of the bolt, that is, at the end of the nut due to the above axial force. **Figure.10.10** shows the outer appearance of the combination of a bolt and a nut with a small pitch difference between the both. This product can be applied not only to conventional bolts but also stud bolts. (2) The second one for "anti-loosening" is shot peening method. When appropriate shots are struck against the thread of a bolt or a nut, some parts of the threads are locally cold-deformed. This deformation acts for anti-loosening force between the both after engagement. **Figure 10.11** shows the outer appearance of the fastener after shot peening about the both. (3) The third one for "anti-loosening" is the inclination of thread of a nut during machining process. The angle of the thread of a nut is inclined between 2-10 degree toward the head of a bolt. This inclination produces the axial force between the both after engagement. In addition, the compressive stress appears at the bottom of the thread of the most dangerous section of a bolt, that is, at the end of the nut due to the above axial force.

The anti-loosening countermeasures by pitch difference, shot peening and inclination of a nut thread have been developed by very simple mechanism and show superior performance.

## Combination of the Above Techniques i.e. Development of “Anti-fatigue & Anti-loosening” Fasteners, Which are Named “Super Screws”

According to the above sessions 3 and 4, the new products are expected by the combination of “anti-fatigue” and “anti-loosening” techniques.

Figure 10.12 shows an example, which combins the CD shaping and the pitch difference techniques. In addition, Fig.10.13 shows another example of the combination product. The shot-peening is adopted to not only a bolt but also a nut in this figure.

Figure 10.14 shows the summary of the above. As can be seen from this figure, the CD shaping is the most excellent method not only for “fatigue” but also for “stress corrosion crack (SCC)” and “delayed fracture (HE)”. On the other hand, the three methods for anti-loosening as shown in the figure are less expensive and useful for reuse of screws. A small countermeasure will be enough for anti-loosening, because the screws show essentially fastening properties when those are appropriately tightened with internal threads.

Anti-fatigue → CD shaping shows the most excellent properties not only fatigue but also SCC and HE

New products

Anti-loosening → ①Pitch difference in both thread between a bolt and a nut
②Shot peening
③Inclination of internal thread

“CD shaping” ＋Anti-loosening①, ②, ③

Brand names:3S bolts(SSS, Super Safety Screw), Anti Break Fastener (ABF), US bolts(USB, Ultra Safety Bolt)

**Fig.10.12 New products by the combination**

The bolt is just an example for development; generally speaking, many persons assume there is no room for development of bolts, when referring to the JIS handbook of bolts, which specifies into e.g. "μm unit".

① Law materials (wire rod)
② Plastic deforming (cold、hot) or machining
③ Heat treatment, surface treatment
④ Fastening process
⑤ Performance (fatigue, SCC, HE) etc.

There remains much room for research and development in every field as shown above!

**Fig.10.14 Suggestions by the preventive methods for bolt failures**

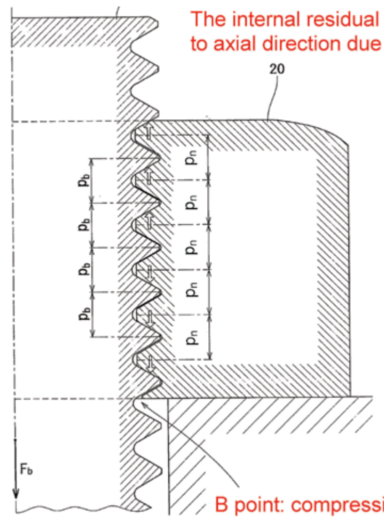



**Fig.10.9 The mechanism of anti-loosening of screw thread**

$p_b$:pitch of bolt、$p_n$:pitch of nut、with small difference between the above, that is, $p_b < p_n$. The axial force acts to widen the distance of screw thread of a bolt and this force effects anti-lossening between the both.

**Fig.10.10 Anti-loosening nut (with single nut, applied to stud bolt)**

Shot peening is applied at the end of a nut or/and screw thread

**Fig. 10.11 Anti-loosening screw by shot peening effect**

**Fig. 10.13 CD shaping ＋anti-loosening nut (anti-fatigue +anti-loosening fasteners)**

**Table 10.2 Merits for bolt users**

| |
|---|
| (1)Screw fastened member with safety and security |
| (2)Decrease of bolt number, or decrease to smaller size→light weight, reduction in cost |
| (3)Maintenance-free after operation etc. |

The new products have the brand names, 3S bolts (SSS, Super Safety Screws), Anti Break Fasteners (ABF) and US bolts (USB, Ultra Safety Bolts).

**Table 10.2** lists the merits for bolt users. As shown in this table, the bolt users can design the screw fastened members with high safety and security under the less expensive price. They can decrease the bolt number or size of the bolts and perform light weight and reduction in cost. In addition, the maintenance-free equipment would be supplied in the market due to the above superior performance.

## Suggestion Under the Development Process of "Super Screw"

As well known, the bolts are one of the most popular industrial products. The reports until now have presented about research and development of performance of bolts. Generally speaking, many persons assume there is no room for development of bolts, when referring to the JIS handbook of bolts, which specifies e.g. into "µm" unit.

**Figure 10.15** shows the suggestions by the preventive methods for the bolt failures. The author refers to only the bolt performance (fatigue, SCC and HE) from the 1st report to the 10th one. When limiting to bolts, there exist research of raw materials (wire rods), plastic deformation (cold deformation or hot deformation) or machining, heat treatment, surface treatment, fastening process etc. except the above fields. Therefore, there remain much room for research and development relating to their fields, respectively. To say the truth, a human's life will inevitably encounter various kinds of problems to be solved. He can also progress himself through corresponding to these problems by "some ingenuity and practice". Then, all kinds of problems could be always resolved in the future, though there exists a certain time lag between occurrence of a problem and its resolution.

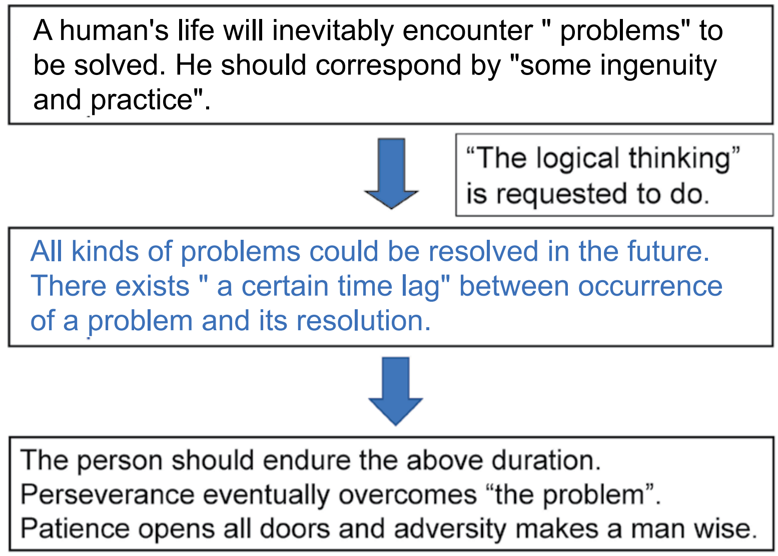



**Fig.10.15 Suggestions according to the process**

## Conclusions

According to the development of high performance of bolts, the following items are summarized:

(1) More than 90% of failure cases are directly or indirectly caused by fatigue

(2) CD shaping will be the most effective for fatigue strength improvement. In addition, this method is also useful for atmospheric brittle fracture such as SCC and delayed fracture (HE).

(3) Anti-loosening method for screw threads can be recommended by pitch difference between a bolt and a nut, shot-peening at screw thread and the inclination of a nut thread.

(4) The "super screw" can be developed to be anti-fatigue and anti-loosening by the combination of the above (2) and (3).

(5) According to the process for development of the "Super Screws", it is found that there remains much room for research and development in various kinds of fields in the world.

## Acknowledgement

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