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# Advantages of Nippon Steel’s Tapered Steel Tube and Its Fatigue Resistance Technology

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## Abstract

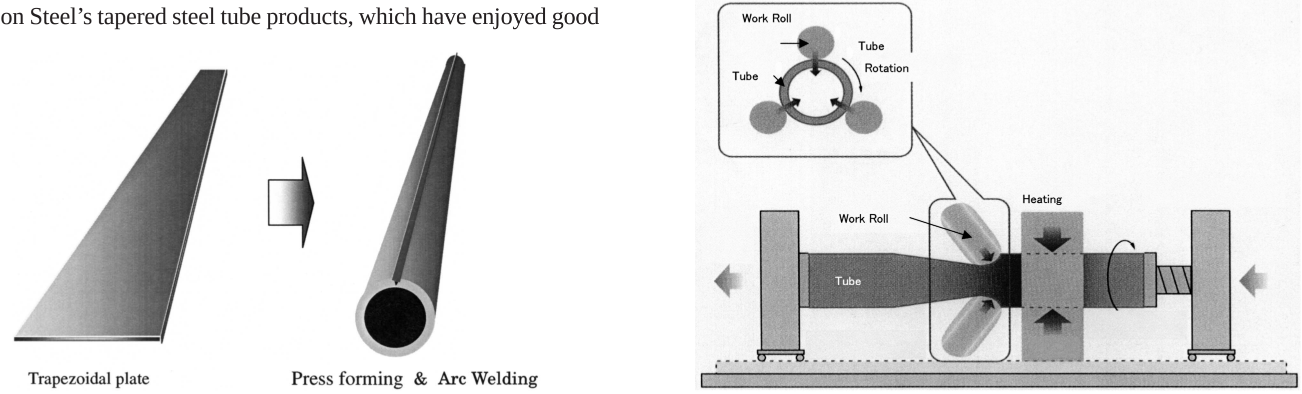
***Since September 1997, Nippon Steel has been producing the tapered steel tubes by its newly invented hot-spinning manufacturing method. Taking advantage of this manufacturing method's capability to create versatile form of tapered configuration, Nippon Steel has developed several unique tubular products and further gave birth to comprehensive fatigue-resistant technology for column structures such as luminaire poles. Best of all, the innovative column base structure has demonstrated landmark performance of fatigue life. This article reports several advantages of Nippon Steel's tapered steel tube products and its fatigue-resistant technology for the column structures.***

## 1. Introduction

Nippon Steel Corporation has developed a technology for producing tapered steel tubes using a hot spin forming method, and has commercially produced tapered steel tube products using this method since September, 1997. The company has developed unique tapered tube products making the best use of the capability of that method to form a wide variety of taper shapes. In addition, it has also developed a fatigue resistance technology for columnar structures such as posts for street lamps. This paper describes the characteristics of Nippon Steel’s tapered steel tube products, which have enjoyed good reputation in the market, and the fatigue resistance technology for columnar structures, focusing mainly on posts for street lamps.

## 2. Nippon Steel’s Production Method of Tapered Steel Tube

A tapered steel tube is produced usually by forming a trapezoidal plate into a conical shape by pressing or other method and welding the butt seam from the outer side, as shown in part (a) of **Fig. 1**. In



**(a) Traditional manufacturing process** **(b) Hot spinning fabrication**

**Fig. 1 Manufacturing process of tapered steel tubes**

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contrast, by the hot spin forming technology that Nippon Steel developed, a tapered steel tube is produced by reducing the diameter of a heated steel tube using forming rolls, as shown in part (b) of Fig. 1. The company began commercial production of tapered steel tube products using this technology in September of 1997. Note that the tapered tube production facility of Nippon Steel forms material tubes into different tapered shapes, while they travel in the longitudinal direction through a heating furnace and a reducing stand equipped with numerically controlled forming rolls.

## 3. Products Taking Advantage of Hot Spin Forming

The hot spin forming method not only makes a wide freedom for taper shapes possible but it also enables production of unique tapered steel tubes such as a variable wall thickness tube and a bottom double-wall structured tube as shown below. The functionality of these tapered steel tube products are explained in this section from the viewpoints of appearance (landscape-friendliness) and improvement of strength including weight reduction and the countermeasures against corrosion at the bottom of poles.

### 3.1 Improvement of appearance

Monotonously tapered steel tubes were used generally for the posts for street lamps, and as a result, landscapes tended to be somewhat featureless. Over the last years, however, it has become popular to feature the landscape of an area with local characteristics such as historical and cultural backgrounds, and street-lamp posts and signposts uniquely designed for the area began, as a result, to enjoy higher demand. Using the hot spin forming method, it is possible to economically produce tapered steel tubes having widely varied curves such as those shown in **Photo 1**, and thus the method can easily respond to the demand for lampposts designed to match a uniquely designed landscape of an area. **Photo 2** shows an example of an entasis-tapered lamppost having a slight convexity in the middle; a uniquely designed lamppost such as this contributes to the landscape design of an area.

### 3.2 Improvement of strength

Again, using the hot spin forming method, it is possible to produce a tapered steel tube having wall thickness that is gradually changed from portion to portion (variable wall thickness tube) and a double tube with a short tube tightly inserted into its large-diameter end (bottom double-wall structured tube). These products are extremely effective in improving the performance of the base portion of a lamppost, at which portion the conditions of load stress and corrosion are the most severe. The advantages of these products are

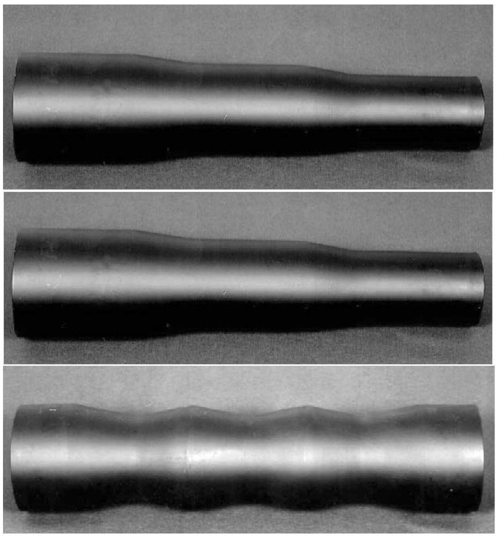


Photo 1 Samples of the taper configurations

Photo 2 Entasis tapered lamp post

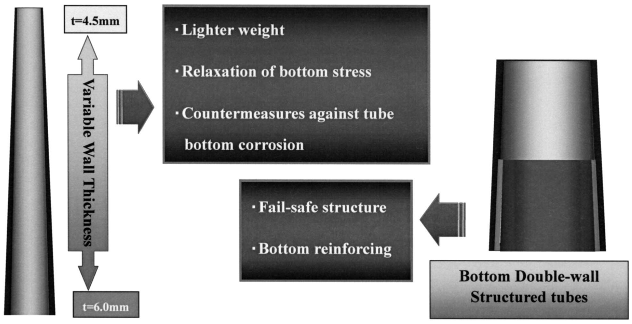
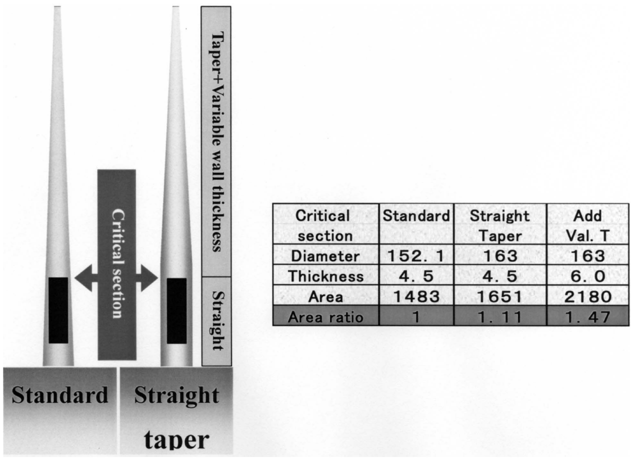


Fig. 2 (a) Strength improvement by the variable wall thickness and bottom double-wall structured tubes



| Critical section | Standard | Straight Taper | Add Val. T |
|---|---|---|---|
| Diameter | 152. 1 | 163 | 163 |
| Thickness | 4. 5 | 4. 5 | 6. 0 |
| Area | 1483 | 1651 | 2180 |
| Area ratio | 1 | 1. 11 | 1. 47 |

Fig. 2 (b) Measures for openings applying the freedom of taper and variable wall thickness tube shown in part (a) of **Fig. 2**. On the other hand, as shown in part (b) of Fig. 2, the freedom of taper shape and the variable wall thickness are effective in strengthening the opening of a lamppost.

## 4. Fatigue Resistance Technology for Columnar Structure

When force, though not strong enough to break a structural member at one stroke, is applied repeatedly, cracks develop and the member is finally broken. This phenomenon is called fatigue failure, and it is considered that fatigue failure is involved as a cause of the failure of machines and structures in many cases. The problem of the fatigue failure of structures resulting from repetitive loads during long use after construction has been attracting attention in Japan, U.S.A., and other developed countries. Various cases have been reported of fatigue cracks occurring to road equipment such as a lamppost or signpost as a result of repetitive loads at short intervals caused by wind and the traffic vibration. In addition to the fatigue resistance measures making the most of the characteristics of the tapered steel tubes produced using the hot spin forming method, Nippon Steel has also developed an innovative reinforcing structure having a high fatigue strength for the base of a columnar structure, the portion of which is prone to fatigue cracks. The fatigue resistance technology is described below.

### 4.1 Portions of lamppost prone to fatigue cracks and fatigue resistance measures

As shown in **Fig. 3**, a fatigue crack occurs in lampposts at (i) the base, (ii) the corners of an opening and (iii) the base of the support arm for lighting equipment. As seen in the photograph of Fig. 3 shows a crack which was formed by repeatedly applying loads to the base of the lamppost. A fatigue crack often develops from the periphery of a welded portion and propagates in the circumferential direction.

As the fatigue resistance measures for a lamppost, on the other hand, it is effective not only to improve the fatigue strength of the portion where a fatigue crack often occurs, but also to prevent the occurrence of resonance of the column and take fail-safe measures to prevent accident, in case a crack occurs.

### 4.2 Fatigue strength improvement measures at base of lamppost

A commonly employed method of installing a lamppost on a bridge or an elevated road is to weld the lamppost to a base plate and fix the base plate to a foundation with anchor bolts. In this structure, however, the base plate alone does not withstand the moment resulting from factors such as the wind force acting on the steel tube and the inertia force of the vibration caused by traffic, and too large a stress is imposed on the welded joint. The measure most commonly practiced against the above has been to weld trapezoidal reinforcing ribs to the steel tube and the base plate (see **Fig. 4**).

However, there have been cases in which a fatigue crack as described in the preceding sub-section occurred near the welded joint at the top end of a reinforcing rib, and in view of the problem, a countermeasure against such a crack has been urgently looked for. In view of the situation and in consideration of the ease of fabrication and performance assurance, Nippon Steel studied countermeasures focusing on methods not involving any special material, welding method or post-welding treatment, and as a result, developed a column base structure (U-shaped rib structure) having remarkably better fatigue strength than similar conventional structures. The U-shaped rib structure is a reinforcing structure for the base of a column in which the conventional trapezoidal reinforcing ribs are replaced with ribs bent into a U-shape as seen in **Photo 3**.

The results of fatigue tests of the U-shaped rib structure is shown in **Fig. 5** together with the fatigue design curves for different fatigue strength classes specified in "The Steel Structure Fatigue Design Guideline and its Commentary[1)]" prepared by the Japanese Society of Steel Construction. The ordinate of the graph represents the amplitude of stress and the abscissa the number of cycles of the stress, and the curves and points in the graph correspond to the number of cycles and the stress amplitude at which a fatigue crack occurred. The graph shows that the fatigue strength of a conventional rib structure corresponds to class G, and that of the U-shaped rib structure substantially to class B. It is understood from the graph, for example, that, whereas a fatigue crack occurs to a conventional rib

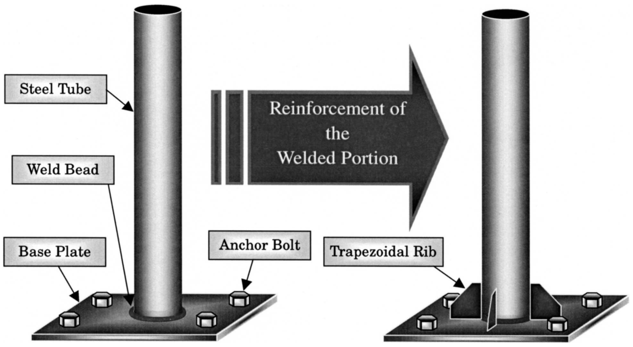


Fig. 4 Reinforcement of the tube-base plate structure by the trapezoidal ribs

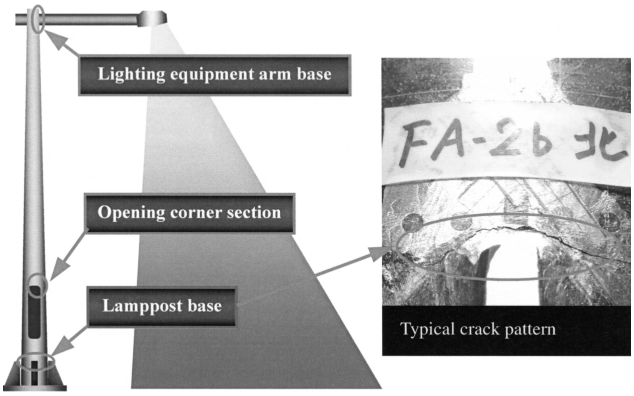


Fig. 3 Critical zones exposed to the danger of fatigue cracking

Photo 3 U-shaped rib structure

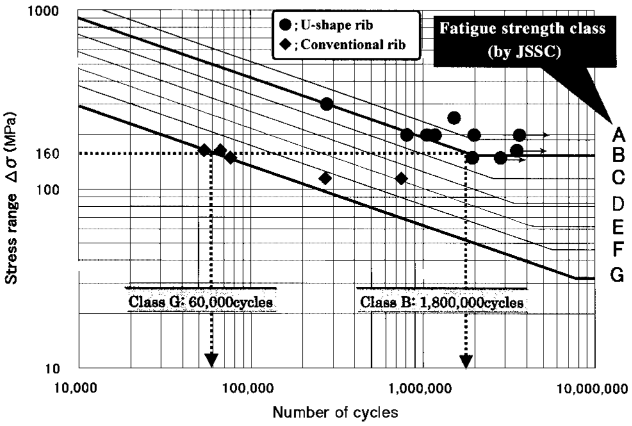


**Fig. 5 The fatigue test result of the pole base structures (JSSC: Japanese Society of Steel Construction)**

structure (class G) at 60,000 cycles of a stress having an amplitude of 160 MPa, the number of cycles at which a fatigue crack occurs can be extended to 1,800,000 by the use of a U-shaped rib structure (class B).

It has been demonstrated through experiments that the U-shaped rib structure has a remarkably improved fatigue resistance as described above. However, since it was necessary to verify theoretically the reasons for the improved fatigue resistance from the viewpoint of reproducibility, we carried out the following examinations:

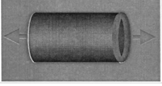
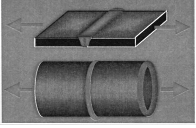
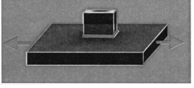
(1) Stress concentration near tops of reinforcing ribs

Trapezoidal and U-shaped ribs were welded to the base of a steel tube and a base plate, loads were imposed on the steel tube, and the stress distribution was measured near the tops of the reinforcing ribs. The results are shown in **Fig. 6**. The stress concentration at the top of a U-shaped rib was remarkably more mitigated than that at the top of a conventional rib. An analysis by the finite element method confirmed the above results.

(2) Residual stress near the tops of reinforcing ribs

As seen in **Table 1**, which is an excerpt from the classification of joint strength according to "the Steel Structure Fatigue Design Guideline and its Commentary[1]" prepared by the Japanese Society of Steel Construction, a joint of class B is a non-welded joint, and it has been considered difficult for a welded joint such as that of a U-shaped rib structure to realize the strength of a class B joint through mitigation of stress concentration only. In view of this, the authors measured residual stress, which has a significant influence over fatigue strength, near the tops of the ribs.

**Table 1 The fatigue strength class of joints ("Steel-structure Fatigue Design Guideline and Its Commentary" by the Japanese Society of Steel Construction)**

| Class | B | F | G |
|---|---|---|---|
| Joint | Non-weld joint<br>Seamless tubes<br> | Butt weld joint<br>(One-side welding)<br> | Gusset weld joint<br> |

Strain gauges were attached near the welded joints of specimen columnar structures to which reinforcing ribs had been welded, the specimen structures were cut with a water-cooling cutter into small pieces, each having one strain gauge, and residual stress was measured based on the change of strain of before and after the cutting. It was found that there was large tensile residual stress near the welded joint at the top of a conventional rib, and on the other hand, the area near the welded joint of a U-shaped rib was surrounded by compressive residual stress, as seen in **Fig. 7**. It had been generally known that there was tensile residual stress near a welded joint, and the compressive residual stress that was measured around the welded joint of a U-shaped rib was quite different from what had been known before.

For the purpose of investigating the cause of the above, the authors analyzed the material deformation after welding by the finite element method, and **Fig. 8** shows the results. The finding was that the steel tube was deformed by the welding of a U-shaped rib in such a manner that the rib wrapped around the outer surface of the tube, and as a result, the outer surface of the tube near the welded joint with the rib was bent locally in such a way that the outer side of the tube was compressed. Thus, it has been made clear that the fatigue strength of the U-shaped rib structure is remarkably improved by the interaction of the mitigation of stress concentration due to the shape of the rib top and the compressive residual stress around the welded joint due to the deformation of the tube resulting from the welding of the ribs.

**Fig. 9** shows an example of the U-shaped rib structure. The ma-

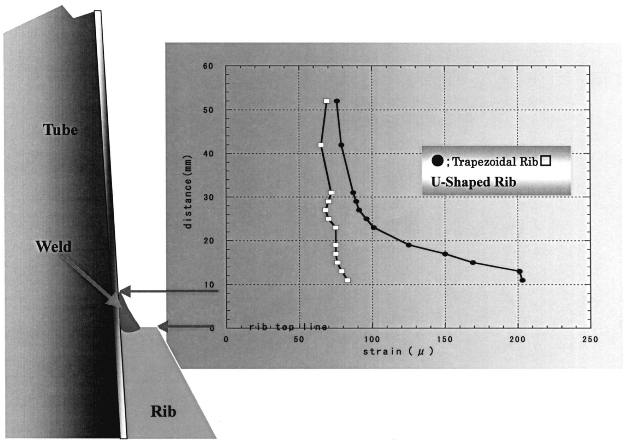


**Fig. 6 Comparison of stress concentration factor**

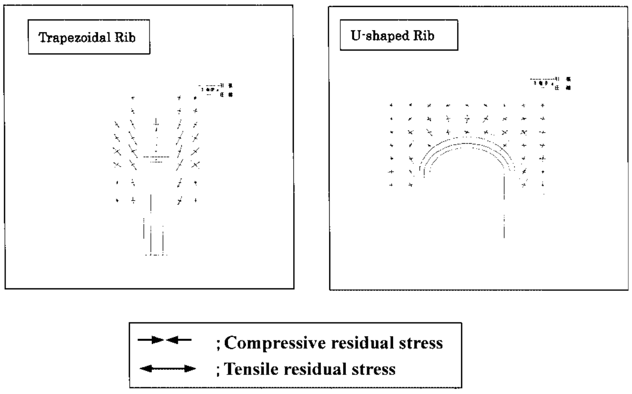
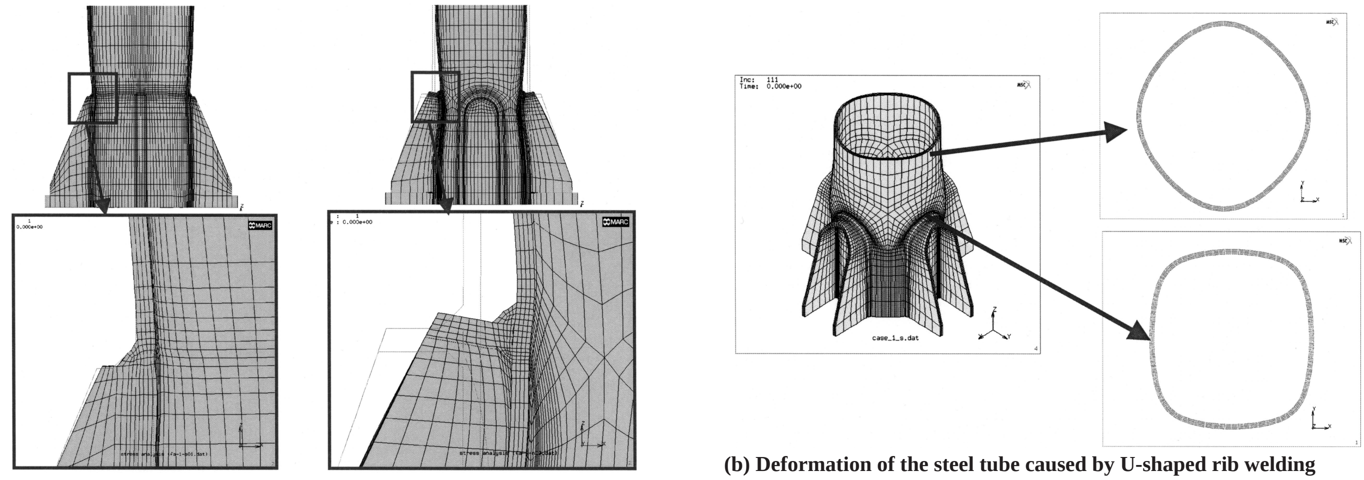


**Fig. 7 Comparison of weld residual stresses**



(a) Deformation of the steel tube caused by rib welding (vertical section)

(b) Deformation of the steel tube caused by U-shaped rib welding (cross section)

Fig. 8 Deformation of the steel tube caused by rib welding

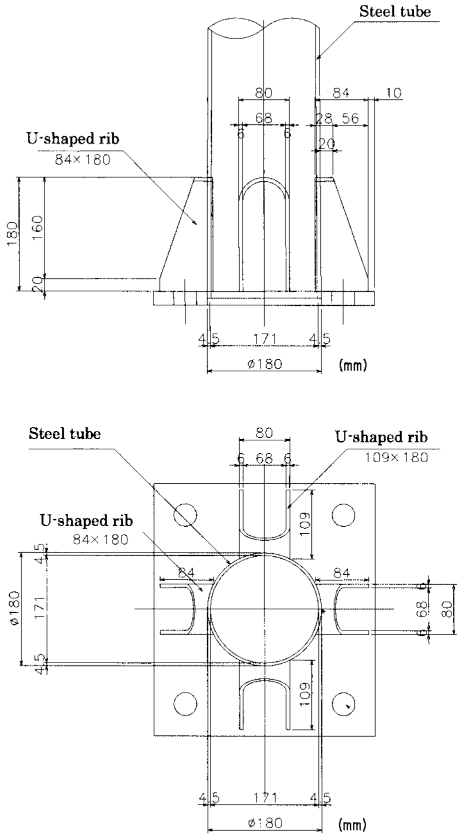


Fig. 9 Detail example of the U-shaped rib structure

terials used are JIS STK 400 and SS 400 for common structural use, and the welding method employed is conventional fillet welding.

The U-shaped rib structure was awarded the Innovative Technique Award of the Japan Society of Civil Engineers for fiscal year of 2002.

### 4.3 Fatigue resistance measures for opening

Usually, a lamppost has an opening for housing a stabilizer or the like inside it. A fatigue crack sometimes develops at the corners of the opening because of the sectional deficiency at the portion and the stress concentration at the corners of the opening or the welded joint of the frame for the lid of the opening. As a measure to make up for the sectional deficiency, increase in the outer diameter and/or wall thickness of the portion is effective, as mentioned earlier. With regard to the stress concentration at the corners, an effective measure is to make the radius of the corners as large as possible.

### 4.4 Resonance prevention measures

Resonance occurs to a lamppost when the frequency of external force due to traffic vibration and/or wind coincides with the characteristic frequency of the lamppost. It strongly vibrates the lamppost, and as a result, very large stress is imposed on the post at short intervals, which sometimes leads to its destruction within a short period of time. Therefore, when there is a possibility of resonance, it is necessary to prevent it from occurring through measures such as designing a lamppost in such a way that the characteristic frequency does not match the frequency of the external force.

The characteristic frequency of a lamppost is determined mainly by the height, sectional rigidity and distribution of mass of the post and mass of lighting equipment and the length of the arm for the lighting equipment. Generally speaking, the height of a lamppost and the mass of the fixture for the lighting equipment are determined by the required illuminance and other conditions of use, and the outer diameters of the post at the base and the top are determined by the road space and the lighting equipment. As a consequence, it is necessary to design the characteristic frequency of a lamppost using, as variables, only the longitudinal distribution of the wall thickness and outer diameter of the post in the portions other than the base and the top. However, when the outer diameters at the base and the top are given, there is no freedom of diameter distribution with the conventional manufacturing method of tapered steel tubes by press forming, which allows only a uniform taper; thus there is little possibility of preventing resonance through the design of the characteristic frequency. Using the hot spin forming method of Nippon Steel, in contrast, a wider degree of freedom is attained regarding the distribution of outer diameter and wall thickness; and it is possible to change the characteristic frequency of a lamppost by changing its shape, for example, as shown in **Fig. 10**. Thus, there are more variables usable for designing the characteristic frequency of a lamppost in a wider range to avoid the resonance with the frequency of traffic vibration and/or other external force.

On the other hand, when it is impossible to take measures for making the characteristic frequency of a lamppost different from the frequency of external force by changing its shape, or to specify the frequency of vibration sources, or when it is necessary to take measures against a higher mode of vibration, it is possible to prevent resonance effectively by installing a vibration control device. Nippon Steel possesses the technology of a compact vibration control device that can be installed at various positions in consideration of the vibration mode or the appearance of the object of vibration suppression, as shown in **Fig. 11**.

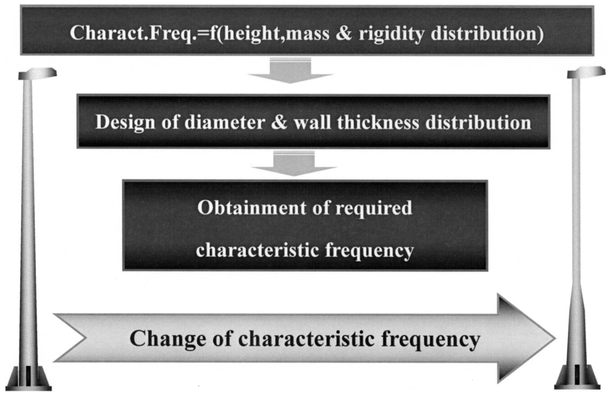


**Fig. 10** Design of characteristic frequency

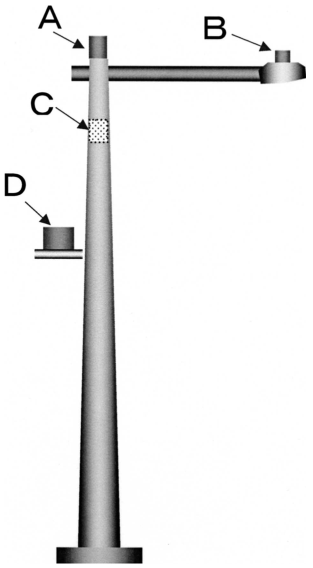


**Fig. 11** Examples of the installation of vibration control devices

For the purpose of confirming the effects of a vibration control device, we carried out the following test using a specimen lamppost with a vibration control device and another without: sinusoidal waves having an acceleration of 20 gal were applied to the specimens through the foundations at the frequency corresponding to the characteristic frequency of the specimen lampposts; the wave application was stopped when resonance occurred; and the change of acceleration over time was measured at the top of each of the lampposts. **Fig. 12** shows the results obtained. In lamppost that were not equipped with a vibration control device, an acceleration approximately 60 times that of the input waves or more was caused by resonance, and the damping after the wave application was stopped was extremely slow. In contrast, in the lamppost with the vibration control device, no abnormal acceleration by resonance was observed and the damping was quick. These results demonstrate that a vibration control device is extremely effective in preventing resonance.

### 4.5 Fail-safe measures

When a columnar structure installed along a road collapses, it is likely to cause significant damage. For this reason, in case that a crack should develop in a columnar structure, it is desirable that the structure does not collapse immediately and safety be ensured by replacing the cracked structure before it collapses and causes any damage.

When a bottom double-wall structured tube presented herein earlier is used, even if its outer tube, which constitutes the main member of the columnar structure, is cracked, the structure is supported by the inner tube and can remain standing for a short period of time, and thus safety is ensured. It has to be noted, however, that the use of a bottom double-wall structured tube must be backed up by periodical inspection of the base of the structure.

### 4.6 Summary of fatigue resistance technologies

As has been explained above, the technologies related to Nippon Steel's tapered steel tubes can be used quite effectively for the fatigue resistance measures of a columnar structure. **Fig. 13** summarizes the relationship between the countermeasures against fatigue and the technology related to Nippon Steel's tapered steel tubes.

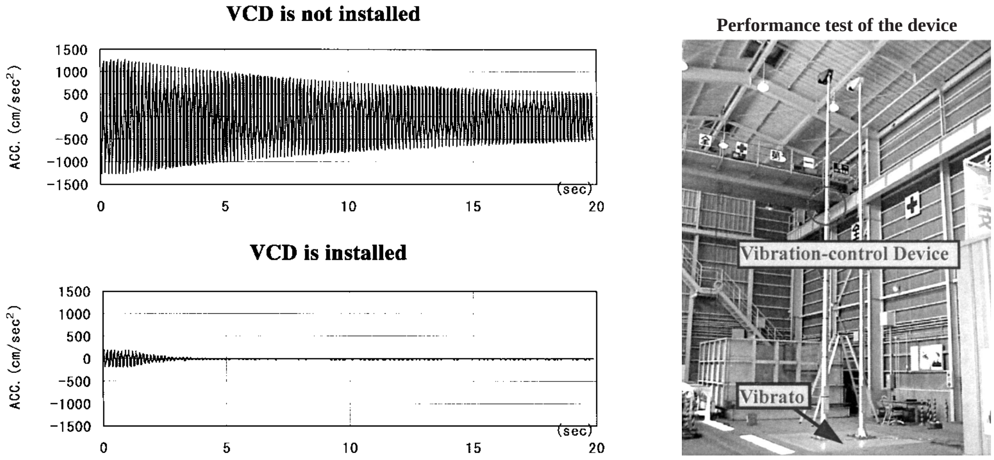


**Fig. 12** The effect of the vibration-control device

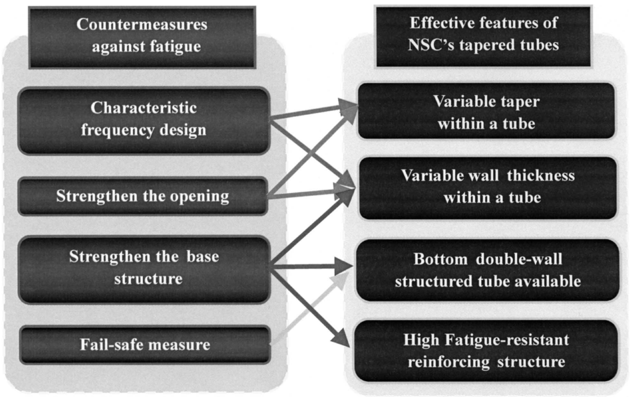


**Fig. 13   Effective features for fatigue resistance**

## 5.  Closing

Nippon Steel's tapered steel tubes, which are produced using the hot spin forming method, are effective in improving the performance of lampposts and other types of columnar structures.  The fatigue resistance of the product is significantly enhanced when they are used in combination with fatigue resistance technology developed by the company.

### References

1) Japanese Society of Steel Construction: Steel Structure Fatigue Design Guideline and Its Commentary. 1st edition. Gihodo, Tokyo, 1993, p.5