TECHNICAL NOTE

Are super-long escalators safe? Lessons learned from the Langham Place escalator incident in Hong Kong

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ABSTRACT

Super-long escalators that are increasingly used in mega-cities take up a large number of passengers, and so their risk of sudden failure draws serious attention. As a case study, on 25 March 2017, an escalator with a 21 m elevation in Hong Kong's Langham Place had its main drive chain suddenly snapped by metal fatigue, causing the escalator to reverse at an accelerating speed. A number of passengers were injured. In this paper, two issues will be discussed: (1) whether metal fatigue of the main drive chain can be detected with conventional protocols, and (2) what safety factor is needed to prevent metal fatigue. Analysis shows that initial fatigue cracks in escalator drive chains may not be easily detected with the commonly adopted maintenance protocol. Also, the time window from the emergence of clear signs of fatigue failure to the sudden snapping of the drive chain may be as short as weeks or even days, versus the common safety inspection intervals of six months. The safety factor to prevent metal fatigue of the drive chain should be at least 7, whereas lower values are allowed. The Hong Kong government has since then changed regulations and adopted additional measures to safeguard escalator failures against metal fatigue.

KEYWORDS Super-long escalators; fatigue failure; main drive chain; safety factor; safety regulations

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1. Introduction

Due to functional and aesthetic requirements, super-long escalators are increasingly used in modern buildings, especially in crowded "mega" cities. In Hong Kong, for example, as at 2017, there were already 64 escalators with height elevation of over 15 m in use (Electrical and Mechanical Services Department, 2017). Unlike an elevator with a fixed capacity, a super-long escalator takes more passengers to a higher elevation, yet the risk of injury or death due to falling when sudden malfunctioning occurs will also be significantly higher.

An incident involving an escalator with an exceptionally high elevation of 21 m (Figure 1(a)) happened in Hong Kong's Langham Place on 25 March 2017 (The Straits Times, 2017). Investigation (Electrical and Mechanical Services Department, 2017) revealed that the incident was due to the snapping of the main drive chain (Figure 1(b)) that supplied power from the driving motor to the movable steps (Figure 2(a)), and the malfunctioning of a "broken chain safety device" which was supposed to be a foolproof device for braking the movable steps in case the main drive chain snaps. As the main drive chain suddenly snapped, the steps became disconnected from the drive mechanism, and the weight of the passengers caused the escalator to roll downward. The incident has caused serious injuries to a number of passengers (The Straits Times, 2017).

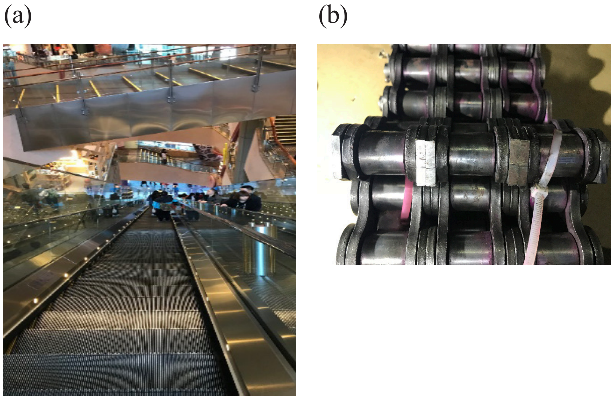


Figure 1. (a) The super-long escalator with a 21 m vertical elevation, involved in the Langham Place incident; and (b) a cut section of the broken main chain drive as inspected by the first author on 2 February 2018 at EMSD.

When incidents like this occur, the maintenance record is among the first items to be investigated, and the corresponding personnel are liable to legal consequences for any malpractices found. However, from the viewpoint of systems reliability, thorough maintenance checks are only effective in preventing failure provided that the stipulated protocols are designed effectively. Furthermore, metal fatigue is a form of catastrophic failure in which the pre-cracks are often not easily detectable. Therefore, in this paper, two important issues are discussed: (1) whether clear signs of metal fatigue of the main drive chain of an escalator can be reliably detectable during maintenance checks, and (2) the minimum safety factor for preventing metal fatigue.

2. The Langham Place incident as a case study

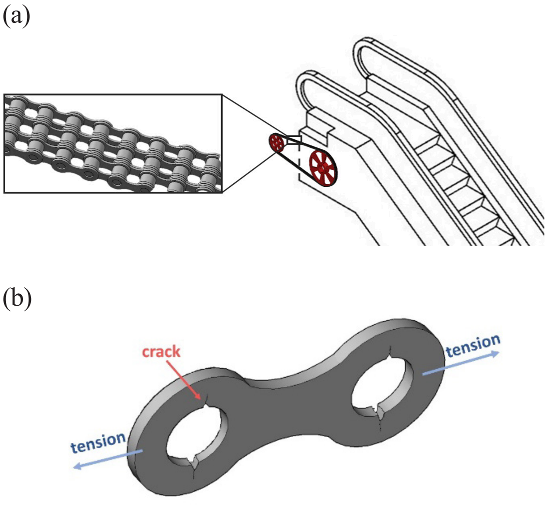
On 25 March 2017, an escalator with an elevation of 21 m running from the fourth to the eighth floor at Langham Place in Hong Kong suddenly stopped, reversed and then sped up, causing the riders to lose balance, fall and pile up at the bottom (Electrical and Mechanical Services Department, 2017; The Straits Times, 2017). Investigations carried out by the Electrical and Mechanical Services Department (EMSD) of the HKSAR Government (2017) revealed that the malfunction was caused by a faulty drive chain, and the broken chain safety device failed to work.

The first author of this paper served as an expert witness in this court case. The main drive chain involved in the incident (Figure 1(b)) had a linked construction as illustrated in Figure 2, and the investigations appointed by the EMSD established the cause of the drive chain failure to be the metal fatigue of the link plates. Figure 3(a) shows the link plates of the drive chain involved in the accident, broken predominantly from fatigue cracks illustrated in Figure 2(b). In Figure 3(b), signs of fatigue failure can be observed on the fractured surface of a broken link plate.

In this paper, two technical issues pertinent to the design of the main drive chain and its maintenance protocol will be discussed. Phrasing them as questions, these are:

(i) Can metal fatigue of an escalator's main drive chain be reliably detectable using the maintenance protocol commonly used in the profession?

(ii) Is the safety factor allowed by government regulations sufficient to prevent metal fatigue?


(a)

(b)

Figure 2. (a) Schematic showing the main drive chain of an escalator; and (b) locations likely for fatigue cracks to initiate in a link plate.

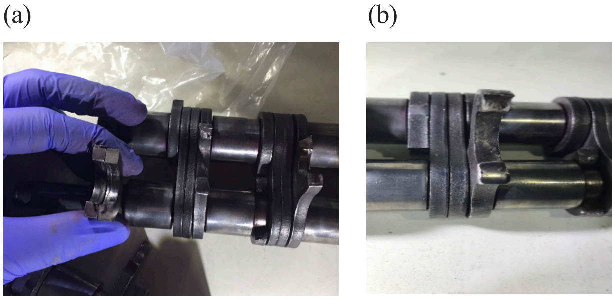

(a)
(b)

Figure 3. (a) Link plates of the drive chain involved in the Langham Place incident, broken from the cracks shown in Figure 2(b); and (b) enlarged view showing signs of fatigue failure on the fracture surface of a broken link plate. Photos taken by first author on 2 February 2018 at EMSD.

3. Inadequacy of existing fatigue inspection protocol

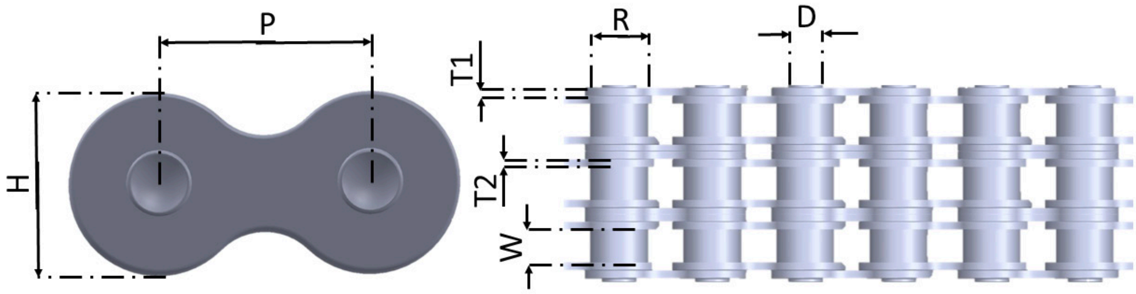
3.1. Location of stress concentration

As shown in Figure 2(a), the main drive chain transmits power from the motor to the movable steps of the escalator. As such, the drive chain is subjected to a predesigned tension during one half of its revolution, and is relaxed during the other half. Due to this form of cyclic loading, the drive chain is prone to metal fatigue. As illustrated in Figure 2(a), the drive chain design has a linked structure comprising link plates connected by pins and bushes. As indicated in Figure 2(b), fatigue cracks are preferentially initiated on the inner side of the link plates in contact with the pins or bushes (Figure 1(a)), where stress concentration is expected to be the highest. Figure 4 shows the geometrical specifications of the ISO R606 24B-3 chain used in the drive chain design of the Langham Place incident. The stress concentration factor in a plate containing a symmetrical hole is principally determined by the aspect ratio of the plate width (H in Figure 4) to the hole diameter (D in Figure 4), and is not significantly affected by the plate thickness T1 or T2 (Pilkey, 2005).

For the link plates involved, the aspect ratio is:

$$\frac{\text{Plate width}}{\text{Hole diameter}} = \frac{H}{D} = \frac{33.00}{14.62} = 2.26 .$$

Figure 5 shows a finite-element calculation of the von Mises stress state in a link-plate shape with a similar aspect ratio of 2.26. In this finite-element simulation, the link-plate is under tension with bearing load acted on the wall of the hole. The absolute values of the von Mises stress are proportional to the applied tensile force on the plate and inversely proportional to the square of its linear dimension, but the ratio of stresses at any two locations is a sole property of the plate shape and is independent of the applied force and the absolute dimension of the plate. It can be seen that on the inner side of the pin hole, marked by the crack



Pitch P (mm)	Width W (mm)	Roller diameter R (mm)	Side-plate height H (mm)	Side-plate thickness T1 (mm)	Side-plate thickness T2 (mm)	Pin diameter D (mm)
38.10	25.40	25.40	33.00	5.20	6.00	14.62

Figure 4. Geometrical specifications of ISO R606 24B-3 chains (FB Chain).

positions in Figure 2(b), the highest stress occurs. The stress concentration factor (i.e. the ratio between the maximum and average stress) at such a location is > 3. Fatigue cracks are therefore expected to initiate at the inner positions of the link plate as indicated in Figure 2(b), and these are locations not visible to a safety inspection personnel.

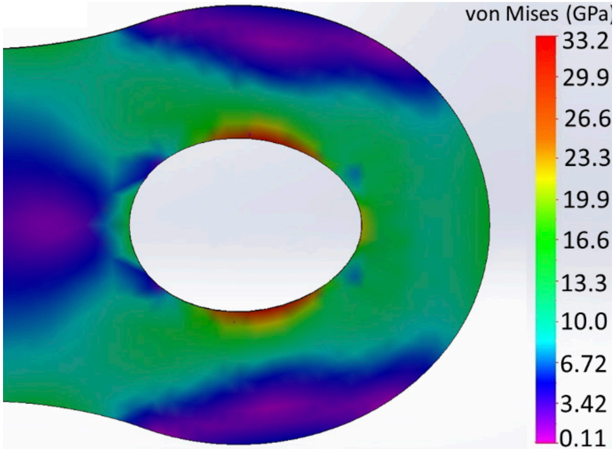


Figure 5. Finite-element prediction of von Mises stress state in a link plate shape of aspect ratio 2.26 between plate width and hole diameter, showing the most highly stressed locations as marked by red. Stress scales are as per the applied loading and only their relative magnitudes are important.

3.2. Common safety inspection procedure

For practical reasons, the linked components of a drive chain cannot be dismantled for individual inspection, and in maintenance protocols commonly designed for escalators, the drive chain is even not required to be removed from the drive system. The maintenance protocol typically stipulates that the drive chain be slacked and its exposed surfaces be cleaned, followed by visual inspection to check that no linked components are damaged or lost, and that the drive chain must run in line with the sprockets of the machine.

In order to assess the chain life, the common maintenance protocol advocates measurement of the length of ten links each time, with a typical rejection threshold of 2% elongation. However, there is no standard way of carrying out the measurement. For example, it is unclear whether the measurement of ten links each time should be a sampling or totality exercise. A common practice in Hong Kong is to make three measurements of ten links each time. Also, it is a legal requirement in Hong Kong that escalators are checked at six months' intervals.

3.3. Assessing chain life by length measurement

The assessment of the residual life of a chain by means of measuring its length is premised on certain plastic deformation being generated in the chain components which then give rise to a permanent elongation of the chain after it has been unloaded. Two main factors may contribute to such a permanent elongation, namely, crack-tip opening displacements (CTOD) of any cracks present, and plastic deformation and material wear at highly stressed locations such as bearing contacts (Smallman and Ngan, 2014). Among these, fatigue cracks are risky as they may lead to catastrophic failure of the drive chain.

The CTOD of an initiated fatigue crack is due to a certain amount of plastic deformation at the crack tip after the crack has been unloaded. The CTOD reflects the ductility of the material, i.e. the higher the ductility, the larger the CTOD. For a given material, the CTOD reaches a characteristic range as the crack is fully developed over time or load history. Table 1 shows values of the CTOD in three types of steels reported in Xia et al. (2013); the typical CTOD varies from 0.2 mm to 0.5 mm.

Table 1. CTOD (in mm) of three steels along different directions (Xia et al., 2013).

	Rolling direction	Thickness direction	Width direction
HT50	0.390	0.240	0.416
HT80	0.401	0.253	0.478
Mild steel	0.423	0.231	0.443

Taking an indicative value of 0.5 mm, the CTOD for a single fatigue crack in a link plate of pitch length of 38.1 mm in the ISO R606 24B-3 design would correspond to an elongation of 0.5/38.1×100% = 1.3%. This is already lower than the 2% rejection limit of the chain. Furthermore, since in the common length measurement protocol, the length of 10 links is measured, a single fatigue crack presents in a 10-link sample would only cause an elongation 10 times lower than the above value, i.e. 0.13%. If no other cracks or significant forms of permanent deformation are present, then a single fatigue crack in a 10-link segment would be practically undetectable by the method of length measurement. The situation is even more unsatisfactory if there are only one or a few fatigue cracks present in an entire drive chain comprising several hundred link plates and pins.

In the course of the investigation of the Langham Place incident, the first author inspected the failed chain. 18 measurements of the link length were made, and each time, the total length of 10 links was measured and the result was divided by 10 to obtain the average length of a link. The results of the measurements were as follows: 38.1 mm, 38.1 mm, 38.1 mm, 37.8 mm, 38.0 mm, 38.0 mm, 38.1 mm, 38.2 mm, 38.1 mm, 38.0 mm, 38.0 mm, 38.1 mm, 37.9 mm, 38.0 mm, 38.0 mm, 38.1 mm, 38.0 mm and 38.0 mm. The mean value of these measurements is 38.03 mm, and the range is 37.8 mm - 38.2 mm. The highest value of 38.2 mm only corresponds to an elongation of 0.26% from the ideal value of 38.1 mm, and this is within the allowable 2%. As mentioned above, the local practice is to make three independent measurements of 10 links each. The chain involved in the incident had 104 links, and so this practice would merely be a sampling exercise of only 30 links over a total of 104, i.e. the sampling rate is only 30/104 = 29%. This may be inadequate for detecting fatigue damage, as they are relatively localised. In conclusion, the measurement of chain length is judged not to be a reliable method for detecting metal fatigue failure. In particular, as a sampling rather than a totality mode of measurement is used, it will be left to random luck for the maintenance personnel to be able to pick up the most damaged links, so as to be alerted of the extent of the damage caused by fatigue.

3.4. Visible signs of metal fatigue vs maintenance intervals

As shown in Figure 2(a), the drive chain design has a triplex structure involving six link plates in three pairs. Therefore, the breakage of one link plate by metal fatigue may not result in the immediate disconnection of the entire chain, thus giving a possible time window for the safety-inspection engineer to identify broken or lost link plates, before the eventual snapping of the drive chain. The question is: what is the likely duration of such a time window versus the stipulated maintenance intervals which are six months in the context of Hong Kong?

To answer the above question, full scale fatigue tests would be needed for each particular chain design and material used. Such data are unavailable at the moment and will take a long time to generate. For a quick assessment of the issue in the interest of public safety, an estimation using Basquin's Law for metal fatigue is adopted. Although the loss of one link plate would not lead to immediate snapping of the entire drive chain, it would definitely result in increased stresses acting on the remaining surviving links. Basquin's Law (Smallman and Ngan, 2014) states that, for a given load-bearing area, the load amplitude P and the number of cycles to failure N are inversely related according to:

$$PN^a=P_0 \,, \tag{1}$$

where a is (the minus of) the fatigue strength exponent, and P_0 is the fatigue load under one load cycle ($N = 1$), i.e. it is the static strength of the component.

Let c be the factor by which the load-bearing area is reduced due to one or more link plates lost as a result of fatigue failure. In the context of the triplex design shown in Figure 2(a), the full number of link plates in a cross-section of the drive chain is six, and so $c = 5/6$ with one link plate lost, 4/6 with two link plates lost, and so on. As stress is defined as load divided by area, reducing the number of intact link plates by the factor c would cause the same stress effect on the chain as reducing the load by the same factor but to have all link plates in place. Hence, for a chain with reduced link plates, its static strength will be adjusted to:

Reduced static strength, $P_0'=cP_0$.

For such a reduced chain, its fatigue law will be:

$$P(N')^a=P_0'=cP_0 \,, \tag{2}$$

where the fatigue strength exponent a is unaffected by the reduction in load-bearing area as it is a material constant. Combining Equations (1) and (2), the fatigue life N' of the reduced chain under the same load P will be given by:

$$\frac{N'}{N}=c^{1/a} \,, \tag{3}$$

where N is the fatigue life with all the link plates present.

Note that N or N' above refers to the fatigue life of a brand new chain with either the full number (i.e. six) of link plates or a reduced number represented by c under the same fatigue load P. In an ideal situation where the link plates share the same load, there would be no good reason for some of the link plates to fatigue-fail more prematurely than others; in practice, some link plates may be weaker than others or subjected to higher loads due to, for example, gear sprocket misalignment, leading to their premature failure. Thus, for a chain starting with the full number of link plates but prematurely losing one after sustaining N_1 load cycles, the remaining life N'_r of the surviving chain is given by Miner's rule (Smallman and Ngan, 2014):

$$\frac{N_1}{N}+\frac{N_r^{'}}{N'}=1\,. \qquad (4)$$

If there were no premature loss of link plates at the N_1th cycle, then the remaining life N_r of the chain would have been $N_r = N - N_1$. Putting this into Equation (4), one obtains $N'_r / N_r = N' / N$, and so from Equation (3), the ratio of the residual lives with and without losing the first link plate prematurely is:

$$\frac{N_r^{'}}{N_r}=c^{1/a}\,. \qquad (5)$$

For steels which are the usual chain materials, the average value of a is known to be around 0.1 (Roessle and Fatemi, 2000; Smallman and Ngan, 2014). Thus, taking a to be this value, the residual life given in percentages predicted by Equation (5) are shown in Figure 6. After the first link plate is lost prematurely compared to others, the residual life is predicted to be reduced to only about 16% of the original; for example, a year would be reduced to two months, six months would be reduced to one month, and so on.

It should be noted that the reduction of residual life to 16% predicted from Figure 6 is actually an upper limit, and the actual residual life should be much lower for the following reasons:

(1) The loss of one link plate will certainly introduce distortions in the structure, creating stress concentrations in some of the surviving link plates nearby so that they may be subjected to stresses much higher than the assumption of equal load sharing in Equation (5).

(2) If some of the surviving link plates are overloaded to beyond their yield strength, then the fatigue behaviour would follow the Coffin-Manson law (Smallman and Ngan 2014), under which the fatigue life would be smaller than that predicted by the present Basquin's Law. Then the Basquin Law prediction of the residual life of the surviving link plates would be an overestimate.

Therefore, after the first link-plate is lost, an original one year of residual life may well be reduced to a few weeks. In fact, it could even be possible that only a few days of the residual life remain. At the end of this residual life, the second link plate would fail by fatigue, and then successive failure of the remaining link plates should accelerate very quickly.

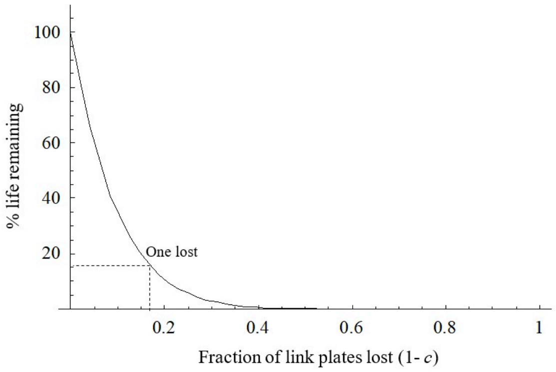


Figure 6. Residual life of drive chain after loss of one or more link plates, predicted by Basquin's Law model with fatigue strength limit $a = 0.1$.

This quick analysis reveals that, because the drive chain is a linked structure, once the first link plate is broken, successive fatigue failure of the link plates would involve a rapidly accelerating process. On this basis, relying on safety inspections at a six-month interval to spot missing link plates from the chain is not a safe method to prevent drive chain breakage.

3.5. Summary

The discussion so far indicates that the common maintenance protocol, in terms of visual inspection and chain length measurement at intervals such as six months, is inadequate for detecting metal fatigue. In fact, it is not certain that if there would be any effective yet feasible method for detecting small fatigue cracks in the link plates in an escalator drive chain. Usual methods for detecting small fatigue cracks in engineering structures include dye penetration, ultrasound or x-ray. However, ultrasound is impractical for chain link plates due to their small dimensions. X-ray would require the dismantling of the drive chain from the mechanism. Although dye penetration may be carried out while the chain is still mounted on the mechanism, this would only allow cracks already propagated to the outer, visible surfaces to be seen. To reveal any initial cracks in the inner parts of the link plates which are likely the case for a drive chain (Figure 2(a)), the entire drive chain needs to be dismounted and the individual link plates dismantled as well, which is not practically feasible.

4. Safety factor for long elevators

Rather than relying on the regular safety checks to spot signs of metal fatigue, it is well known among reputable chain manufacturers that a high enough safety factor should be used to safeguard against metal fatigue. The safety factor is defined as:

$$\text{Safety factor} = \frac{\text{Tensile strength}}{\text{Design load}} . \qquad (6)$$

One manufacturer Renold Jeffrey in the United States, for example, suggests a safety factor of 8 to avoid metal fatigue in general (Renold Jeffrey Design Guide 29). At such a safety factor, the design load will be below the endurance limit at which the fatigue life will be infinite. Its design guide (Renold Jeffrey Design Guide 29, p. 216) states that "Loads below the endurance limit will result in infinite fatigue life. The failure mode will then become wear related, which is far safer, since a controlled monitor of chain extension can take place at suitable planned intervals". This also implies that monitoring of chain extension is only for detecting material wear, not fatigue, as discussed in Section 3.3 above.

It is commonly known that for ferrous materials, loads below the endurance limit will result in infinite fatigue life (Renold Jeffrey Design Guide 29; Smallman and Ngan, 2014). The failure mode will then become wear related, which is far safer since a controlled monitor of chain extension can take place at suitable planned intervals. In practice, if a load ratio of tensile strength to maximum working load of 8:1 is chosen, then the endurance limit will not normally be exceeded (Renold Jeffrey Design Guide 29). Careful consideration of the expected maximum working loads should be given since these are often much higher than what the designer may think. It is also a requirement that any passenger lift applications in the United States are designed with a safety factor of not less than 10 (Renold Jeffrey Design Guide 29).

As for requirements in the ISO standard, for a 24B-1 simplex chain that barely satisfies ISO 606, the tensile strength is 160 kN and the dynamic strength, i.e. the endurance fatigue limit, is 19.7 kN. For a 24B-3 triplex chain, the ISO 606 standard specifies the tensile strength to be 425 kN, but does not specify the minimum dynamic strength. Assuming that the ratio of the dynamic strength between the 24B-1 simplex and 24B-3 triplex chain is the same as that of the tensile strength, for a 24B-3 triplex chain that barely satisfies ISO 606, the minimum safety factor to avoid fatigue would have to be $425/(19.7\times425/160) = 8.1$. This is like the value of 8 suggested by Renold Jeffrey in their design guide (Renold Jeffrey Design Guide 29, p. 216).

In Japan, the Japanese Industrial Standard (JIS) requires explicit consideration of the working load of the chain against the fatigue endurance limit, termed the "maximum allowable load", which is many times lower than the tensile strength rating (U.S. Tsubaki, Inc., 1997). Therefore, chain manufacturers such as Tsubaki provide examples in their design guide to show that the "maximum allowable load" is not to be exceeded (U.S. Tsubaki, Inc., 1997), and both the tensile strength ratings as well as the maximum allowable loads are specified in their products (Figure 7). As this manufacturer's chains are compatible with, and actually exceeding, ISO 606 requirements, fatigue may still be avoided at safety factors lower than 8 or so. From the data in Figure 7 for their triplex chains, it can be seen that for tensile-strength rating up to about 500 kN, the maximum allowable strength for avoiding fatigue is about 1/6 of the tensile strength rating. Furthermore, it is stipulated that the design load should be set lower than the maximum allowable load by at least 10%. Therefore, to avoid metal fatigue, the safety factor has to be at least 6.6, for the type of Tsubaki chains described (U.S. Tsubaki, Inc., 1997).

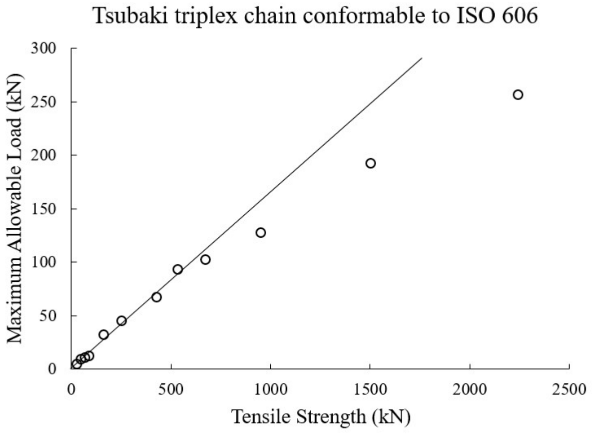


Figure 7. Relation between maximum allowable load (dynamic strength) and tensile strength rating in ISO 606, for triplex chains supplied by a chain manufacturer Tsubaki (U.S. Tsubaki, Inc., 1997). Straight line shows a ratio of 1:6.

Table 2 compares the safety factors stipulated in various occasions discussed so far. The minimum safety factor to safeguard metal fatigue is 7 or so, according to different sources (Renold Jeffrey Design Guide 29; U.S. Tsubaki, Inc., 1997).

Table 2. Minimum safety factors needed to avoid fatigue.

	Safety factor to avoid fatigue
Triplex chains that barely meet extrapolated ISO 606 requirements	> 8.1
"Renold Jeffrey" design guide	> 8
Tsubaki 24B-3 triplex chains	> 6.6

In Hong Kong, the *Code of Practice on the Design and Construction of Lifts and Escalators* issued by the EMSD (2010) requires that in relation to an escalator, the safety factor of chains shall be at least 5. Based on the design calculation by the manufacturer of the escalator in the Langham Place incident, a safety factor of 5.1 was used for the drive chain, based on the tensile strength rating of 425 kN for an ISO 606 R24B-3 chain, and a design load of 83.8 kN on the chain, i.e.

$$\text{Safety factor} = \frac{\text{Tensile strength}}{\text{Design load}} = \frac{425\text{ kN}}{83.8\text{ kN}} = 5.1\ .$$

This value of safety factor is therefore compliant with regulations in Hong Kong, but, is lower than the minimum values to safeguard against fatigue risks. At a safety factor of 5 or so, a chain that could be sourced in the market (such as those in Table 2) is likely to operate within the load regime where metal fatigue will eventually happen.

Although the Hong Kong legislation at the time of the Langham Place incident specified the minimum safety factor for escalator chains to be 5 (Electrical and Mechanical Services Department, 2010), in the European standard for the construction and installation of escalators and moving walks (BS EN115-1:2017, section 5.4.1.3.2), there is also a requirement on fatigue: "The design of all driving elements shall be of nominally infinite fatigue life".

In the example of a crowded city like Hong Kong, there are more than 9,000 escalators in use (Research Office, Legislative Council Secretariat, 2017), of which only 64 or so have a height elevation of over 15 m (Electrical and Mechanical Services Department, 2017). Super-long escalators are therefore very rare, and this highlights the questions of whether manufacturers have gained enough experience to properly design safety-ensuring systems and maintenance programmes, and whether legal requirements for safety margins are sufficiently updated for these ultra-high escalators. Unlike an elevator, an escalator that rises to a greater height can also take on more passengers. In the present case study of the Langham Place incident, the escalator has 110 steps between the loading and landing platforms, and so assuming a maximum of two passengers standing on each step, the full capacity would be 220 passengers at a given time. With the potential of such a large number of passengers and the very high elevation of 21 m, the risk of injury or death due to sudden malfunctioning would be significantly higher than an escalator of a typical height. It is therefore of prime importance that the maintenance protocol, safety-check frequency and programme, and, most importantly, the design safety factor requirement, can safeguard against such a risk. In particular, it is alarming that the safety factor of the main drive chain can be allowed to be as low as 5, without explicit stipulation on metal fatigue consideration in the design. In sound engineering practice and legislation, there is no good reason to allow a machine to be designed to operate under a known risk – in this case metal fatigue which has been well understood in the engineering profession. Therefore, in view of the Langham Place incident, there is an urgent need for escalator manufacturers to review the safety and maintenance requirements of super-long escalators, and at the same time, for governments to review the design codes to avoid metal fatigue of the drive components.

5. Fatigue life assessment of main drive chain

While new escalators can be designed with safety factors of 7 or higher to avoid metal fatigue, for existing escalators designed with lower safety factors, their main drive chains are prone to fatigue failure as discussed above. Such a risk can only be fundamentally removed by changing the drive chain to a thicker one with a sufficient safety factor, but this would also require the complete reconfiguration of the plant room which may not be possible for practical reasons. For these escalators, regular safety checks need to be strengthened, and in addition, the fatigue life of their drive chains should be estimated, and replacement schedules should be set accordingly as a mandatory requirement. Here, how the fatigue life of the escalator design involved in the Langham Place incident can be assessed is illustrated as below.

Basquin's Law in Equation (1) is used to estimate the fatigue life of the drive chain in the Langham Place escalator. From the design specifications of the manufacturer of the escalator in the Langham Place incident (Table 3), static strength $P_0 = 425$ kN, and the design load on the drive chain is $P = 83.8$ kN. From Equation (1), assuming a value of 0.1 for the fatigue strength exponent a (Roessle and Fatemi, 2000; Smallman and Ngan, 2014), the number of cycles to failure N at the design load can be estimated as:

$$N=(P_0/P)^{1/a}=(425\text{ kN}/83.8\text{ kN})^{1/0.1}=10^7\ .$$

Table 3. Design specifications of the escalator in the Langham Place incident.

Safety factor for drive chain	5.1
Main drive chain force	83.8 kN
Breakage load of main drive chain	425 kN
Speed of escalator steps	0.5 m/s
Pitch diameter of main drive chain sprocket, d_{mcs}	946.209 mm
Pitch diameter of step chain sprocket, d_{scs}	865.922 mm
Main driving chain pitch	38.1 mm
Number of pitches in drive chain	104

From the design specifications in Table 3, the rotational period of the drive chain is $\frac{104\times0.0381}{0.5}\times\frac{d_{scs}}{d_{mcs}}=7.25$ seconds. Assuming that the escalator was operated for eight hours a day at the full design load, the number of daily load cycles on the drive chain would be 8×3600/7.25 = 3971. The full design load used by the manufacturer is based on a load of 181.4 kg on every step of the escalator, which is just about the weight of two grown up males, i.e. it should not be a severe overestimation. Therefore, the number of cycles at full design load is 3971×30 = 119130 per month. A fatigue life of 10^7 estimated above would therefore correspond to $10^7/119130 = 84$ months, or seven years.

From evidence given in the court hearing, the drive chain was actually in use for seven years and seven months before the incident, and so the estimation of ~7 years is fairly accurate. However, in general, the estimated fatigue lifespan depends sensitively on a number of factors including the precise value of the fatigue strength exponent a in Equation (1) and the actual operation cycles under the full design load, which are difficult to be obtained accurately. Therefore, a safety margin should be set in for the estimated lifespan; say, in the Langham Place case, the drive chain should have been replaced at the end of the fourth or fifth year, rather than leaving it to last for more than seven years.

6. Recommendations

Summarising the above, for chains designed with a safety factor smaller than 7, it is recommended that an analysis similar to Section 5 be carried out to estimate the fatigue life. Then, before reaching the fatigue life, regular inspections should be carried out as are now done. However, on approaching the fatigue life (say, on the fourth or fifth year for a seven-year fatigue life), fatigue can happen very suddenly, and so regular checks placed at realistically affordable intervals would not be reliable. The chain should then be replaced, even though no apparent damage is revealed by the present inspection protocol.

For new escalators, designing the main drive chains with a safety factor larger than 7 is recommended. Then, fatigue should not occur, and regular checks can be used to monitor the general elongation and wear of the chain.

7. Epilogue

Since the Langham Place incident and the authors' communications with the relevant authorities, the Hong Kong SAR Government has revised the design codes for escalators and adopted additional measures to safeguard against metal fatigue failure. In particular, in addition to requiring a minimum safety factor of 5, in the new design code for escalators that has become effective in June 2020, there is an extra requirement of "all driving elements to be designed with nominal infinite fatigue life", to align with the EU standards. Also, the main drive chains of escalators over 15 m long need to be replaced at intervals not more than 6 years (Electrical and Mechanical Services Department, 2019).

8. Conclusions

Initial fatigue cracks in escalator drive chains may not be easily detected with the commonly used maintenance protocol of visual inspection, since such cracks are likely to be underneath visible surfaces, or by measuring the chain length, since fatigue damage is highly localised. Although fatigue failure of the first link plate may not lead to immediate snapping of the entire drive chain, the time window in between can be as short as weeks or even days. Therefore, relying on safety inspections at intervals of months to spot structural integrity such as missing link plates is also not an ideal method to prevent drive chain breakage.

Metal fatigue in drive chains is best prevented by setting a high enough safety factor during design. The minimum safety factor to prevent fatigue is estimated to be 7 or so, depending on the fatigue endurance limit of the drive chain that can be procured. When the chain is operating outside the fatigue regime, length measurement will then be a good way to monitor general wear and tear, and then replacement can be scheduled accordingly.

In Hong Kong where the legal requirement for the minimum safety factor of escalator drive chains is set lower than 7 or so, the legislation has been strengthened to safeguard against fatigue failure.

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