TRELLEBORG

Applying the right Correction Factors

WHITE PAPER

Introduction

In recent years, rubber manufacturing industries have experienced an evolution in both the emergence of contract mixers, and new manufacturers in low cost countries becoming mainstream manufacturing hubs. Additionally, a wider range of ingredients are available for rubber compounding.

These changes, especially those related to rubber compound, are a significant departure from tradition. It is critically important that the industry understands the impact these changes in ingredients have, not just on the rubber compound, but also the downstream effect on fender performance and lifecycle.

Current research by Trelleborg Marine Systems into the changing properties of rubber compounds used in fender systems and the move towards non-traditional fillers (such as those explored in depth in our 2012 whitepaper, “Fenders: why it’s not so black and white”) show factors such as Velocity Factor (VF) and Temperature Factor (TF) are now highly likely to have a material impact on engineering design and fender selection, as well as further implications for the design of other wharf infrastructure.

In addition, current research by Trelleborg Marine Systems highlights that the performance and lifecycle of marine fenders vary dramatically based on the type of rubber used – natural or synthetic, and virgin or recycled – and within that, the compound composition of the rubber.

As such, it’s essential that the market takes steps to educate itself and become aware of the implications of this evolution.

It is important that specifiers avoid pitfalls such as putting trust in supplier documentation, without understanding the composition of the fenders they procure.

Previous research showed that “lower cost” fenders typically contained a higher percentage of recycled rubber than their “high quality” competitors, as well as high percentages of non-reinforcing white filler. The performance characteristics of the two varied dramatically.

The aim of this paper is to explore in greater depth the impact that rubber compound composition has on Velocity Factor (VF), Temperature Factor (TF) and fender lifecycle.

Rheology: non-linear engineering

The behaviour of rubber under stress is unique. It is recognised in the theory of "Rheology", which describes the flow of polymers under stress. Through rheology, we understand that the stress or reaction force produced by a rubber fender during compression not only depends on strain level, but also on strain rate (how quickly the strain is induced).

This means that when a rubber fender is compressed, the resultant reaction force and energy absorption are greater when the compression occurs at a higher speed.

Currently, performance data from most manufacturers is presented with a berthing velocity of 2-8 cm/min, and rarely is there advice on the effects of temperature or velocity. The difference between this and actual real life conditions (those used for the design of fender systems and wharf structures) needs to be accounted for in the engineering design.

VELOCITY FACTOR (VF)

Velocity Factors & Fenders

Typically, normal berthing velocity of vessels is from 20 mm/sec to 500 mm/sec. In a perfect world, fender manufacturers would test at actual berthing velocities to determine the performance of the fenders. However, in practice this is exceptionally difficult given the size of investment in equipment and range of fenders to be tested.

PIANC's 2002 "Guidelines for the Design of Fender Systems" highlighted the importance of VF in design and selection of fenders, and introduced guidelines for calculating and reporting VF.

For a given velocity, there are two factors that have the greatest influence on VF. Strain Rate (compression time) and the type of rubber used in the fender.

Strain Rate

Compression time is a direct measure of strain rate and, if all other parameters are kept constant, strain rate has a significant impact on VF.

For a given velocity, a large fender needs more time to be compressed than a smaller one. Subsequently, at the same berthing velocity, the strain rate on a large fender and, importantly: the magnitude of VF, will be lower than on a smaller fender.
(See figure two on page 8.)

Type of Rubber used

The second factor that greatly influences VF is the type of raw rubber used in compound formulation. Trelleborg Marine systems has undertaken extensive testing using actual high speed compression and results show that given the same compression time, a fender comprised of 100% natural rubber (NR) will have a lower velocity factor (VF) than a fender comprised of 100% synthetic based rubber (SBR).

This is due to differing rates of Stress Relaxation between NR and SBR and relates to differences in the microstructure in the respective polymer chains.

SBR is commonly used in marine fenders in conjunction with, or as a replacement of, NR: improving longevity, high temperature performance and some physical properties. Testing has shown that VF is highly dependent on the NR/SBR blend ratio and the overall rubber compound formulation.

Therefore, it is necessary that manufacturers and designers understand the factors that affect VF and are able to provide competent commentary in relation to the application of VF in their rubber compounds and fender designs.

The Impact of VF

The magnitude of the VF in most cases will have a material impact on fender performance characteristics (Reaction Force and Energy Absorption) at normal design berthing speeds, and by default the design of fender system components (frontal frames, chains and anchors) as well as the wharf structure.

Using VF, performance figures should be adjusted to account for design berthing velocity. In general we would expect increased reaction force, and a corresponding increase in energy absorption.

The fender system design will need to account for the increased reaction force in relation to restraint chain and fixing anchor design, as well as forces applied to the frontal frames. In addition, the increased reaction force loads will need to be reviewed against the structural design of the wharf (quay wall, or dolphin etc.).

Simply, it's imperative that manufacturers incorporate guidance on the effects of VF on their fenders.
When comparing catalogue figures from different manufacturers, it's essential to ensure VFs are applied to calculate RPD (Rated Performance Data) to ensure you're comparing like for like.

TEMPERATURE FACTOR (TF)

The Theory Behind TF

Elastic properties are measured by stress and strain behaviour, and expressed by “modulus” of the rubber compound.

The reason designers of marine structures should be concerned about the elasticity of rubber is that it is a measure of stiffness (modulus). Reaction force and thus energy absorption are directly proportional to rubber stiffness.

This stiffness changes dramatically with temperature, which, in turn, has a tremendous effect on fender performance.

Although the presence of these long polymeric chains is essential for rubber to exhibit elasticity, it is not enough to guarantee the properties of the rubber compound. It’s also essential that the rubber chain has sufficient mobility at the desired temperature of use. Ideally, rubber elements for fender systems should be tested on a case by case basis, in accordance with the temperatures they will be subjected to in the field.

Why do we need a temperature factor (TF)?

Any factor that has an effect on the stiffness of the rubber compound must be taken into consideration in the design of fender systems.

In general, decreasing strain rate has the same effect on stiffness as increasing temperature, i.e. it effectively makes rubber softer.

The effect of strain rate has been discussed in velocity factor (VF). However, to accommodate the variations in temperature that fenders will be exposed to under actual operating conditions, it’s essential to apply TF during the fender design and selection process. (See figure three on page 8.)

Similar to VF, TF is highly sensitive to the type of rubber used – NR or SBR, or a blend of the two, as well as the inclusion of recycled rubber. It therefore varies with fender type and from manufacturer to manufacturer.

Temperature Factor is vital in understanding changes to reaction force and energy absorption of fenders in normal operating conditions, and plays an important role in both the design of berthing structures and the selection of fender systems.

Typically the engineering design will review possible minimum and maximum temperature conditions likely to be experienced. At high temperatures, the fender is effectively softer and as a result, will have a lower energy absorption capacity, whilst at low temperatures the fender is harder and will by default have higher reaction forces which must be accounted for in the design of the fender components as well as the wharf structure.

Effect of VF and TF on fender performance:

Let’s take the example of an SCN1000 E2.5 fender to look at the impact of both TF and VF. The Rated Performance Data (RPD) is shown in the table below. We will ignore the fender tolerance for this example:

FENDER	SCN1000 E2.5
Reaction at rated deflection	1043 kN
Energy at rated deflection	540 kNm
Testing Speed	2-8 cm/min
Test temperature	23± 5 ºC
Compression angle	0 deg

Given a typical range of berthing velocities and temperatures at the berth, we’ll explore below the impact on fender performance of both of these factors.

Design and selection of fender systems will review both Energy Absorption and Reaction Force. The aim is to select a suitable fender that does not exceed the reaction force limits under normal operating conditions, whilst providing more than the minimum energy requirement.

The maximum reaction force occurs under a different set of operating conditions to the minimum energy absorption. For example, the highest Reaction Force will occur with the highest velocity and lowest temperature, whilst the lowest energy will occur with the slowest velocity and highest temperate.

For a typical design we might expect to experience the following condition:

- Design berthing velocities of between 20 and 160 mm/s,
- Operating temperature range of between 10°C and 40°C.

VF: At 160 mm/s

Assuming steady state deceleration, the compression time (t) is:

$t = d / (f \times v_d) = (0.72 \times 1000) / (0.74 \times 160) = 6.1$ sec

t = compression time

Vd = initial berthing velocity

f = deceleration factor (peak reaction force accurs at ~ 30% deflection where there has been a deceleration due to energy absorption. f represents the factor associated with the deceleration.)

(Trelleborg Marine Systems has conducted actual high speed compression testing to validate its VFs. Information on these effects can be discussed with Trelleborg Marine Systems' Engineers).

Based the strain rate for this compression time, the VF is calculated to be:

VF = 1.16 (Please note this relates ONLY to Trelleborg Marine Systems' compounds.)

VF: At 20 mm/s

$t = d / (f \times v_d) = (0.72 \times 1000) / (0.74 \times 20) = 48.64$ sec

VF = 1

TF: At operating range of 10°C to 40°C

TF (10°C) = 1.076 and
TF (40°C) = 0.929.

So, under actual operating conditions, the performance will be:

Maximum Reaction Force Conditions:
(@ 160 mm/s & 10°C)

$$\text{Reaction Force} = R_{CV} \times VF \times TF$$
$$= 1043 \times 1.16 \times 1.076$$
$$= 1302 \text{ kN}$$

Energy absorption: (@ 20 mm/s & 40°C)

$$\text{Energy Absorption} = E_{CV} \times VF \times TF$$
$$= 540 \times 1.00 \times 0.929$$
$$= 502 \text{ kJ}$$

Therefore, under the extremes of the possible operating conditions the effects of temperature and velocity are summarised at the end of the page.

The same fender performs differently depending on the factors applied. The magnitude of the factor depends on the rubber compound used and size of the fender. Both have a significant effect on fender performance under real operating conditions, and subsequently, on the design and selection of the system and of the berthing structure.

It's imperative that these factors are considered during the design of fender systems. Again, care should be taken when comparing products from different manufacturers, as factors will differ depending on the type of rubber compound used during production.

Lifecycle Determination

The design of port facilities in general has an expectation of a design life exceeding 25 years. This by default flows down to expectations for the design life of the fender systems. In modern times the saying "You get what you pay for" is increasingly the catch cry when cheap purchases fail to meet expectations. It is the view of Trelleborg Marine Systems that to achieve a long and full life, fender systems need to be designed properly and treated as an investment, rather than as a commodity product.

The life expectancy of fender systems is highly dependent on the critical rubber component, more than any other component or accessory. The durability and subsequent lifecycle of rubber fenders depends on many factors. The type of rubber used, compound formulation, environmental conditions in the field, heat, ozone and operational use and mechanical damage.

Oxidative aging, a process described as the change in rubber properties over time, is one of the main issues impairing the functionality of rubber fenders over their lifecycle.

SCN1000 E2.5	CV (1 mm/s, 23°C)	Velocity Factor (VF)	Temp Factor (TF)	Performance (In reality)	% Change
Reaction Force	**1043 kN**	**+ 16%**	**+ 7.6%**	**1302 kN**	**+ 24.8%**
Energy Absorption	540 kJ	0%	- 7.1%	502 kJ	- 7.1%

The mechanisms that produce oxidative aging depend not only on the degradation agent (oxygen, Ozone, UV radiation etc) present in the environment but also the type of rubber used (virgin or recycled), and the types of additives used in the compound formulation.

Trelleborg Marine Systems has developed analytical techniques to identify the rubber composition of fenders, making it possible to accurately determine the presence of ingredients that are critical to the life of the fender. These include percentages of recycled or virgin rubber as well as non-reinforcing fillers, amongst others.

Actual case studies conducted globally by Trelleborg Marine systems for multiple clients have provided anecdotal evidence that fenders utilizing a high percentage of recycled rubber are, in general, more prone to mechanical failure and accelerated environmental degradation.

Based on the following case study, we aim to show the effect of higher percentages of recycled rubber on the longevity of fenders.

Samples Chosen for Testing:

Two types of samples were chosen for testing.

- Test pieces made from rubber compounds with 20% recycled rubber.
- Test pieces made from rubber compound with 75% recycled rubber.

The theory of longevity

The theory behind the estimation of life cycle (for rubber elements) is based on the Arrhenius relationship, a widely accepted model used to determine the relationship between reaction rate and temperature.

The chemical reaction rate normally increases with an increase in temperature. By exposing test pieces to a series of elevated temperatures and measuring the property changes, the relationship between the oxidative aging reaction rate and temperature can be deduced.

Reaction rate is a constant modified by the ratio between the activation energy and the gas constant and absolute temperature. It has a non-linear relationship between the activation energy and absolute temperature. (See figure four on page 8.)

International standards used for testing:

TEST	Standard used
Elongation at break	ASTM D412 die C
Aging in hot air oven	ASTM D573
Estimation of life	ISO 11346

Results

SAMPLES	Predicted life cycle at		
	20 ºC	**30 ºC**	**40 ºC**
Rubber compounds with 20% recycled rubber	57 years	18 years	6 years
Rubber compounds with 75% recycled rubber	6 years	2 years	1 year

A predicted life cycle of 18 years in a temperature of 30°C means that the elongation at break of this sample will reduce to 70% of its original value in 18 years. Once elongation at break has dropped to 70% of its original value, rubber will start to crack, indicating the end of the life of the product.

It is evident from the study that fenders made of higher percentages of recycled rubber will have a significantly shorter life. The selection of rubber compound ingredients is perhaps a more critical aspect in ensuring long life is achieved, especially in environments with adverse operating conditions.

Conclusion

Changes in the rubber fender market in recent years include changes to compound formulations and new ingredients, many of which have occurred without the necessary understanding of the impact on engineering design or life expectancy.

Despite PIANC recommending the application of TF and VF, these are really only the starting point in the design and selection of rubber fenders. Many suppliers (trading houses) and manufacturers either do not make the necessary investment in research and development to underpin their claims, or apply far too low factors to their products. Many actually copy factors that are not relevant to their compound formulations.

Anecdotally, the evidence in the market points to a far greater failure rate of fenders, and in our opinion this is solely as a result of underperformance of the fender due to compound formulation changes over the last 10 years.

It's essential that designers, operators and owners of port infrastructure begin to educate themselves and take a more considered approach when procuring this mission critical equipment. The need to apply engineering principles and standards to the critical rubber component – and to apply them at the same level as those applied to steel fabrication – is long overdue.

It's imperative that this culture of procurement based solely on up-front cost, without consideration of rubber grade and compound formulation, is not allowed to continue.

Appendices

FIGURE ONE

VF is defined as below:

VF for Reaction Force, $R_{vcf} = \dfrac{\text{Reaction force @ real berthing speed}}{\text{Reaction force @ 2-8 cm/min}}$

VF for Energy: $E_{vcf} = \dfrac{\text{Energy @150 mm/sec}}{\text{Energy @1 mm/sec}}$

FIGURE TWO

Compression time is dependent on the following:

- Initial Berthing Velocity (V_i)
- Deflection Displacement of the fender (d) = Fender Height x Rated Deflection

Compression time is defined as:

$$\text{Compression time } (t_{Berthing}) = \frac{\text{(Fender Height X Rated Deflection)}}{\text{Deceleration speed } (V_d)} = \frac{dc}{V_d}$$

Vd = 0.74 *Vi

e.g. : $t_{Berthing}$ for 1000 mm height AN E1 fender (rated deflection 52.5%) with 150 mm/sec initial berthing velocity $= \frac{d}{V_d} = \frac{1000 \times 0.525}{111} = 4.7$ sec, whereas $t_{Berthing}$ for 500 mm height AN E1 fender (rated deflection 52.5%) with 150mm/sec initial berthing velocity

$$= \frac{d}{V_d} = \frac{500 \times 0.525}{111} = 2.36 \text{ sec.}$$

Therefore, according to the Strain rate theory, the magnitude of VF for AN500 fender will be larger than AN1000 fender.

FIGURE THREE

Defining TF

Technically TF can be defined as given below:

$$TF_t = \frac{R_t}{R_{23}}$$

Where,

TF_t : Temperature factor

R_t: Reaction force at temperature t ºC at deflection 35% or below

R_{23}: Reaction force at 23 ºC at deflection 35% or below

Maximum reaction force occurs typically at around 35% deflection for buckling type of fenders and above 35% deflection the behavior of fenders is nonlinear due to the buckling effect. Therefore, the ratio of reaction forces should be taken below 35% of deflection to calculate the TF in the range where the deflection vs. reaction force is linear.

FIGURE FOUR

$$K(T) = Ae^{\frac{-E}{RT}} \quad \text{------------- (1)}$$

Taking logarithm in both sides of the equation:

$$\text{Log } K(T) = \text{Log } A \frac{-E}{RT}$$

$$\text{Log } K(T) = C \frac{-E}{RT} \quad \text{------------- (2)}$$

Where:

C: Log A

K(T): the reaction rate

E: activation energy

R: Gas Constant

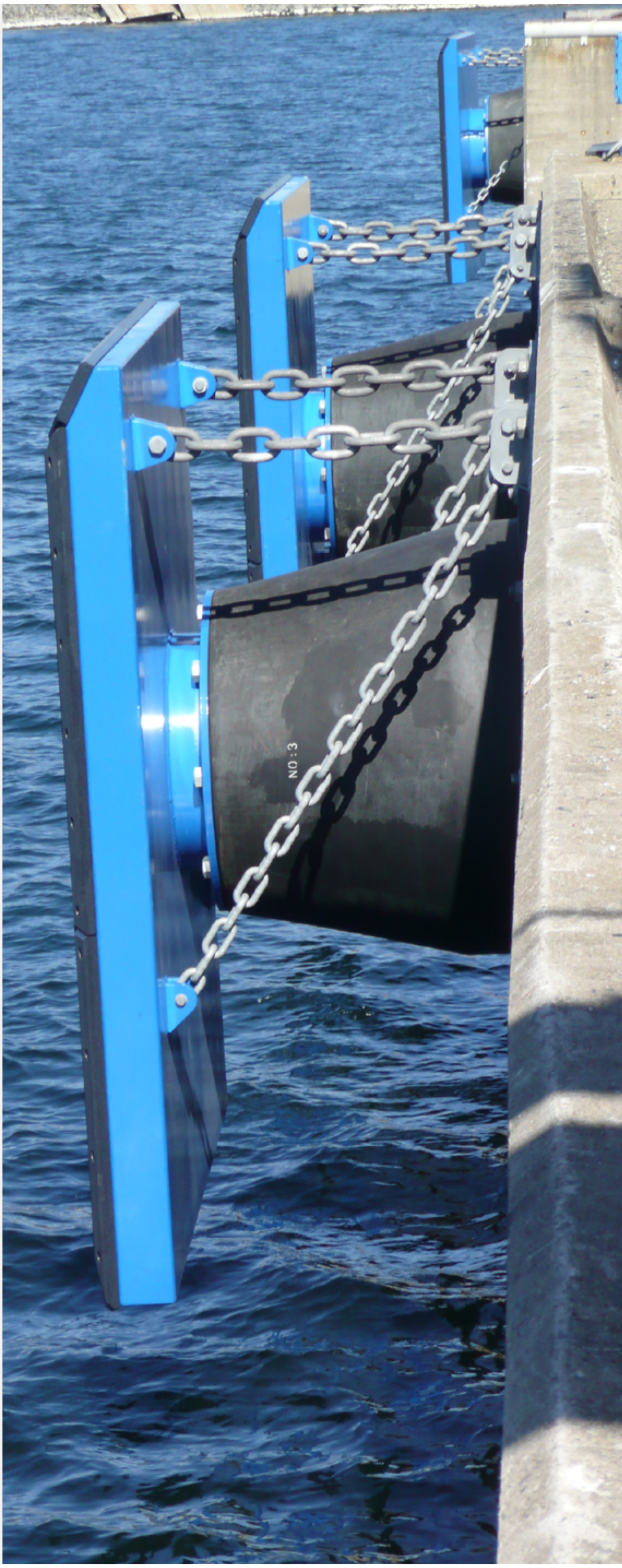
T: Absolute temperature

A and C: Constants

Application of the Arrhenius relation in our samples,

Test Procedure and assumptions:

- We assumed that oxidative aging, a chemical process, was responsible for the elongation at break reducing from its unaged (original) value at higher temperature
- Unaged (original) elongation at break was measured for both the samples at room temperature
- The rate of oxidative aging reaction of both the samples was obtained from the change in the value of elongation at break from the original, in a 2 days interval for 32 days at 80/90/100 ºC. Elongation at break at different temperatures was plotted against log hours for each exposure time for both the samples
- Through our experience, we assigned 70% drop of the value of elongation at break as threshold value below which fender shows cracking and considered as end-of-life
- The threshold value was plotted on the same graph as a straight line at 30% (remaining fraction of the original value)
- Log hours from the X-axis were obtained from the intersection of threshold line and elongation at break line at different temperatures
- Arrhenius plot was then constructed by plotting log hours against reciprocal of absolute temperature. A straight line was obtained by joining three points
- The line thus obtained was extrapolated to 20/30 and 40 ºC (as reciprocal of absolute temperature) to obtain the log hours from the Y-axis
- Log hours converted back to years indicates the predicted life at that particular temperature



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