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FULL-SCALE TESTS OF TRANSPORTING PIPELINE SECTIONS – A REVIEW AND CONSEQUENCES TO OUR INVESTIGATIONS

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Abstract: Hydrocarbon transport pipelines' safe operation is an economic and environmental interest. These pipelines are typically designed for static loads, but during their long-time operation – due to pressure changes and environmental impacts – they are also subject to cyclical loads. The individual pipe sections are connected by girth welds, which represent potential sources of hazards in terms of damage. In order to assess the reliability of girth welds, full-scale tests are carried out under simple and complex loads. The purpose of this article is twofold. On the one hand, summarize the full-scale tests on transmission pipelines, with special attention to the tests on girth welds; on the other hand, based on this, draw conclusions for the design and implementation of our own full-scale tests.

Keywords: *transporting pipeline, full-scale test, girth weld, complex loading condition*

1. INTRODUCTION

A lot of efforts have been made to estimate the mechanical performance of pipes subjected to longitudinal plastic stresses as a result of the progress of strain-based design (SBD) for pipelines. Ductile ripping from a girth weld flaw is a common failure condition that defines tensile strain capacity (TSC). Because of factors like welding bevel angles and high-low misalignment (MA), this condition is difficult to predict. *Table 1* shows the characteristics of incidents on transporting pipeline girth welds investigated by the Institute of Materials Science and Technology at the University of Miskolc.

The fundamental failure mechanics, which involve localized plastic deformation and material shredding, is equally challenging to model. Stationary crack modelling and the damage mechanics technique are two typical finite element analysis (FEA) techniques. Both strategies have disadvantages. It has been noted that stationary crack modelling can underestimate TSC because it is unable to account for all of the plasticity that happens in the area of a tearing fracture and does not explicitly simulate tearing (Fairchild, Crapps, Cheng, Tang & Shafrova, 2016), (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014). When it comes to the damage mechanics technique for modelling the tearing process, there is a lot of discussion on how to tune/calibrate the micro-mechanical parameters that the model relies on.

Table 1
Main data of selected catastrophic girth weld damages on gas transporting pipelines

ID	DN, mm	PN, bar	Material ID (API 5L) (API, 2018)	Operation years	Cause(s) of the failure
No1	400	63	Grade B and X52	54	crack in a repaired girth weld
No2	600	60	X52 and X60	45	crack in a repaired girth weld caused by the repair and the cyclic loads
No3	800	64	X65	33	crack initiated in the meeting point of a girth weld and the spiral weld, caused by geometrical irregularities and cyclic loads

The question is, what should an engineer do when the failure scenario is complex, and modelling approaches are limited? There are often two solutions to this puzzle, one of which is significantly more critical. The first step is to execute many modelling runs and sensitivity analyses covering all of the variable ranges in depth. This entails hundreds of modelling runs for models with a half-dozen variables (as is the case for TSC prediction). While such exercises can help with recognizing patterns (for example, as MA grows, TSC decreases), they are insufficient to build a credible model on their own (Li, Gong, Lacidogna, Deng & Wang, 2021). The second and far more critical solution is that model results must be compared to full-scale experiments (FSTs). In applied mechanics, this has always been the authoritative answer and the answer for TSC prediction. In addition, both theoretical and practical approaches to structural integrity require the investigations of both structural elements and complete structures (FSTs) (Lukács, Nagy, Harmati, Koritárné & Kuzsella, 2012), (Koncsik, 2019), (Koncsik, 2021).

The purpose of this article is twofold. On the one hand, we summarize the full-scale tests on transmission pipelines, with particular attention to the tests on girth welds; on the other hand, based on this, we draw conclusions for the design and implementation of our own full-scale tests.

2. THE RELEVANCE OF THE FULL-SCALE TESTING

2.1. Short overview of full-scale pipeline testing

Full-scale pipe strain tests involve stretching and bending a section of pipe to failure. The fundamental metric is strain capacity, which refers to how much longitudinal strain the specimen can withstand before failing, which is commonly referred to as maximum load. It is possible that the specimen is a parent pipe or that it has one or even more girth welds. Artificial flaws (from a practical point of view notches) are common in girth welds; thus, including different degrees of welding joint MA might be beneficial. When there are girth weld faults, the failure scenario frequently involves ductile ripping from the defect till the remaining ligament fails. To reflect service conditions, the specimens might be compressed (Zhang & Maddox, 2014). A schematic of a characteristic FST pipeline section with girth welds is shown in *Figure 1* (Fairchild, Crapps, Cheng, Tang & Shafrova, 2016), (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014). The cost of specimen design and manufacture, followed by testing and analysis, may go into the tens of thousands of USDs (millions of HUF) for each test. A single test might take weeks or months to complete. The preparation of a specimen with known and high qualities is the most significant component of test specimen design and production.

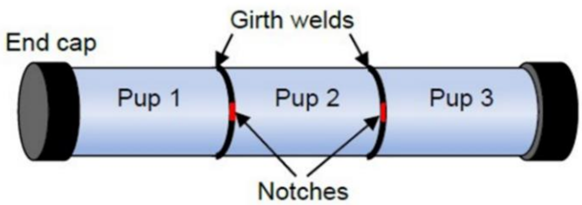

Figure 1. *Schematic structure of a full-scale pipeline section (specimen)* (Fairchild, Crapps, Cheng, Tang & Shafrova, 2016), (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014)

The true qualities of the specimen cannot be determined since it was damaged during testing. To create data indicative of the specimen, small-scale experiments on additional material are required, and the results of these tests are crucial inputs for TSC model predictions. The design in *Figure 1* is created by the layout in *Figure 2* (Fairchild, Crapps, Cheng, Tang & Shafrova, 2016), (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014).

Full-scale testing also necessitates the use of specimen instrumentation. Longitudinal strain and notch opening are monitored using instrumentation. Linear variable displacement transducers (LVDTs) are commonly employed to monitor strain, while clip gages are utilized to measure crack mouth opening displacement (CMOD). Figure 3 (Fairchild, Crapps, Cheng, Tang & Shafrova, 2016), (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014) is an example of an effective instrumentation layout. A possible unrolling of the pipe specimen is depicted in the diagram. To detect global strain over the specimen length, three massive LVDTs are employed. The anchor points are as practicable as near the end cap confluence with the pipe specimen. The FST’s strain capacity is defined as the average of these LVDTs at maximum load (Yang et al., 2022). Additionally, shorter LVDTs are placed on each pup, and these LVDTs are used to detect possible non-uniform straining. The application of scribe lines (ultimately scribed mesh) is the least technical (but most beneficial) of all strain monitoring methods [*Figure 3* (Fairchild, Crapps, Cheng, Tang & Shafrova, 2016), (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014)].

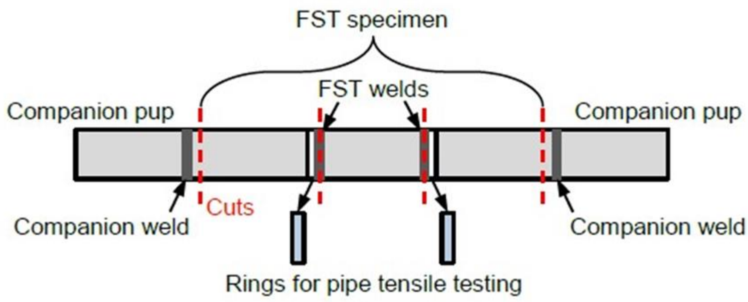

Figure 2. *Preparation strategy for FST sections and associated materials*
(Fairchild, Crapps, Cheng, Tang & Shafrova, 2016),
(Fairchild, Shafrova, Tang, Crapps & Cheng, 2014)

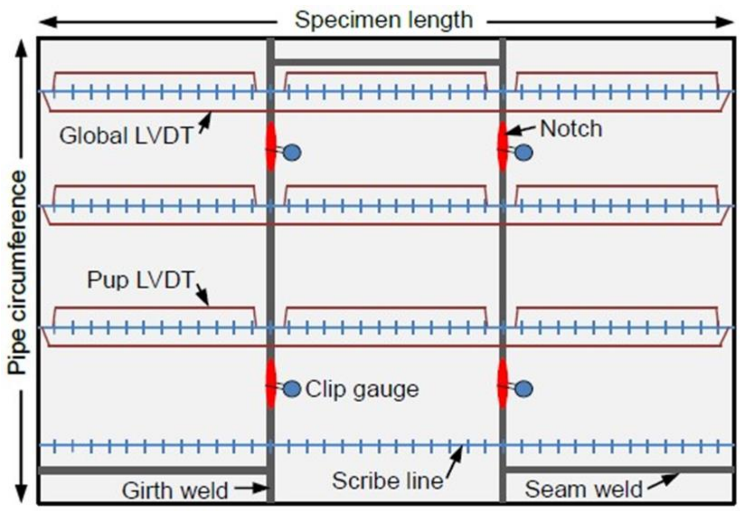

Figure 3. *Instrumentation for FST (unrolled pipe view)*
(Fairchild, Crapps, Cheng, Tang & Shafrova, 2016),
(Fairchild, Shafrova, Tang, Crapps & Cheng, 2014)

The structure shown in *Figures 1–3* can, of course, be differed from, and in some cases should be. In the case where the FST tests are performed on replaced pipe sections, there is only one tested girth weld on the pipe section, and no notches are applied. The purpose of the tests is to analyse the damage that has occurred and to draw conclusions about the remaining lifetime (Lukács, Koncsik & Chován, 2022).

Regular (100–150 mm) crosshairs on scribe lines can be placed along the same linear routes as the LVDTs. To quantify strain, the distance between the marks and the thickness of the wall at the markings are measured before and after the test. Data from scribe lines may be utilized to double-check LVDTs and track non-uniform strains. The process of assessing the data post-test to gain a complete picture of specimen performance is just as vital as test preparation. This necessitates a cross-validation of LVDT and scribe line data. Non-uniform straining should be looked for during the activity. If this is suspected, further ultrasonic wall thickness measurements may be beneficial. The CMOD data should be compared to the results of the other notch assessment methods (fractography, sectioning). One of the main objectives is to see if any notches were "active" throughout the test, indicating that ductile tearing has started. The CMOD data is typically easy if the specimen does not fracture. If the specimen cracks, the first step is to pinpoint the location of the fracture, which is usually the notch with the highest CMOD at the conclusion of the test. It should be highlighted that brittle fractures have been recorded farther from the notch with the biggest CMOD [see *Figure 4* (Igi, Muraoka & Masamura, 2013)].

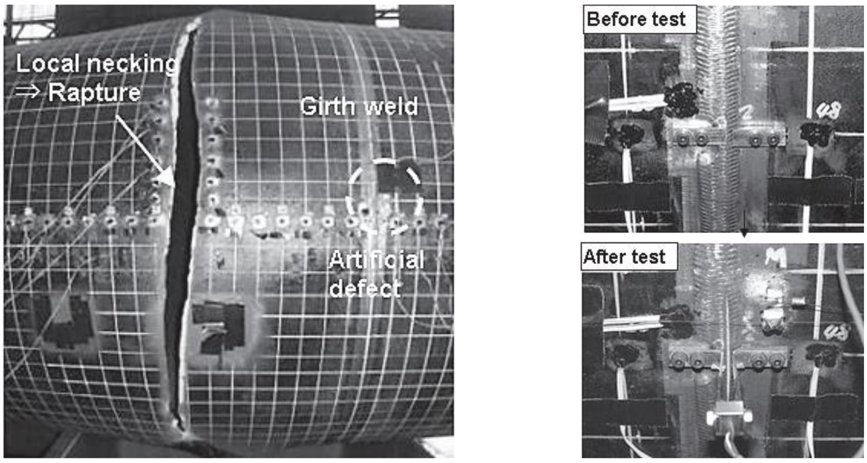

Figure 4. *Fracture appearance of a girth weld after FST on meshed pipeline* (Igi, Muraoka & Masamura, 2013)

Fractured specimens might be difficult to interpret; fractography is a valuable tool for gaining a better understanding of the failure event and, in many cases, assessing the importance of the FST. Fractography is used to detect the location of quick fracture initiation, whether crack propagation was ductile, brittle, or mixed, and the crack propagation direction. The texture, geometry, and varied shades of grey revealed on the fracture surface frequently allow the failure event to be recreated.

2.2. The importance of high-quality full-scale testing data

Full-scale testing is a large-scale representation of experimental fracture mechanics. FST specimen preparation is more complex than, for instance, Charpy impact or crack tip opening displacement (CTOD) tests due to several variables. However, the toughness and crack propagation resistance curves of the material were related to the geometry of the specimen; the fracture toughness decreases with the increase of the constraint level of the specimen (Yang, et al., 2022), (Thaulow, Østby, Nyhus, Zhang, & Skallerud, 2004) [see *Figure 5* (Yang et al., 2022)].

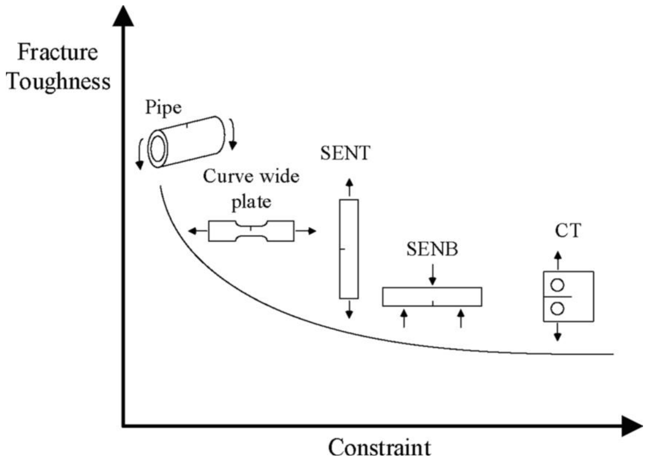

Figure 5. *Schematic diagram of specimen geometry effect on fracture toughness* (Yang et al., 2022)

During the preparation of the full-scale pipeline test, the amount of material is substantial, and specimen manufacturing necessitates extensive welding. As a result, the likelihood of material property variation and the occurrence of unintentional flaws is enhanced. Furthermore, notch insertion in the heat-affected zone (HAZ), which must be done "blind" into the specimen surface, is extremely challenging (Igi, Muraoka & Masamura, 2013), (Elyasi et al., 2021), (Wei, Jin, Pei & Wang, 2021), (Xuan et al., 2016).

One overarching concept and two hypothetical examples may be used to demonstrate the necessity for high-quality FST data. The guiding assumption is that developing predictive TSC models is a difficult applied mechanics task and rigorous model validation using FSTs is essential because present models are relatively new and broad SBD pipeline service experience is lacking. Consider the following scenario: a forecast from a relatively recent TSC model does not match the result of an FST, and no evident testing abnormalities are discovered. Is the model incorrect, or is there an issue with the test? If the model is defective, the next step is to upgrade. If the test fails, failure analysis is necessary to uncover the root reason. The defect geometry may not have been as expected, or a brittle fracture may have happened, in which case the test should be disregarded. In view of the time/cost required to conduct these tests, there will certainly be opposition to abandoning an FST, but it is occasionally essential. Consider a second scenario in which an FST is performed as a final proof test of project materials, and the model forecast differs from the outcome. A similar dilemma arises: is it better to solve a model problem or a test problem? If the pipeline project is on a tight schedule, this scenario might be challenging, especially if the test falls short of the goal TSC. Concluding that project materials do not fulfil design goals is a risk that may be avoided by paying close attention to all FST aspects. Late project adjustments are limited, and they frequently include more stringent defect acceptance criteria, which can be expensive. Unless addressed through failure analysis [see, e.g. (EPRG, 2014)], problematic FSTs constitute road-blocks to advancement because they raise unresolved issues about whether bad predictions were generated by an erroneous model, a flawed FST, or a mix of both.

2.3. Model development vs. project work

The aim to isolate the influence of particular factors on strain capacity is a fundamental difference between FSTs for model development and FSTs for project work. A sequence of FSTs for model building, for example, might be developed with steadily rising defect sizes while keeping all other factors constant. The aim will be risky if variables other than defect size alter accidentally. It can be challenging to maintain consistency in crucial aspects such as weld strength, which affects mismatch, given the volume of test specimen manufacture.

As a result, because 1G-rolled, automated welding techniques are exceedingly consistent, they are excellent for FSTs connected to model making. Because of the size of the specimens, the importance of test variable control cannot be overstated. Engineers have been battling welding-induced fracture differences in specimens (Charpy V-notch, CTOD) orders of magnitude less than full-scale pipe strain tests for decades. Because of the amount of girth weld material in an FST and the possibility for fluctuation along the circumference, all elements of specimen fabrication, especially those impacting strength or toughness, must be closely monitored.

When the FST is employed for project work, however, the welding technology will be determined by the pipeline fabrication processes. The 5G position is usual for field welding; however, semi-automatic or manual methods may also be employed. With project processes, a larger degree of girth welding variation is unavoidable; nonetheless, this variation is allowed because the purpose of project work is to proof test any variances that may occur within the authorized techniques (Bolton, Semiga, Tiku, Dinovitzer & Zhou, 2011), (Chapetti, Otegui, Manfredi & Martins, 2001) (Bastola et al., 2016).

3. Design and preparation of the specimen

3.1. Bending vs. tensile loading:

For actual pipes, strain-based loading will nearly always result in bending; nonetheless, tensile loading is recommended for full-scale testing for various reasons. If the goal of the test is to develop a model, sample statistics are critical, and it is best to include as many notches as feasible without risking other objectives (see *Figures 1* and *3*). For example, two endplates and two loading tongues are included in a pipe model; each is represented by reference nodes with eccentricity from the pipe's longitudinal axis. To replicate properly welded connections, the tie constraint was applied to link the endplates to the shell pieces. Finally, the experimentally applied eccentric loading was modelled using a tie constraint connecting the loading tongues to the endplates with eccentricity. The CMOD values for tests and models were compared (Elyasi et al., 2021) (see *Figure 6*).

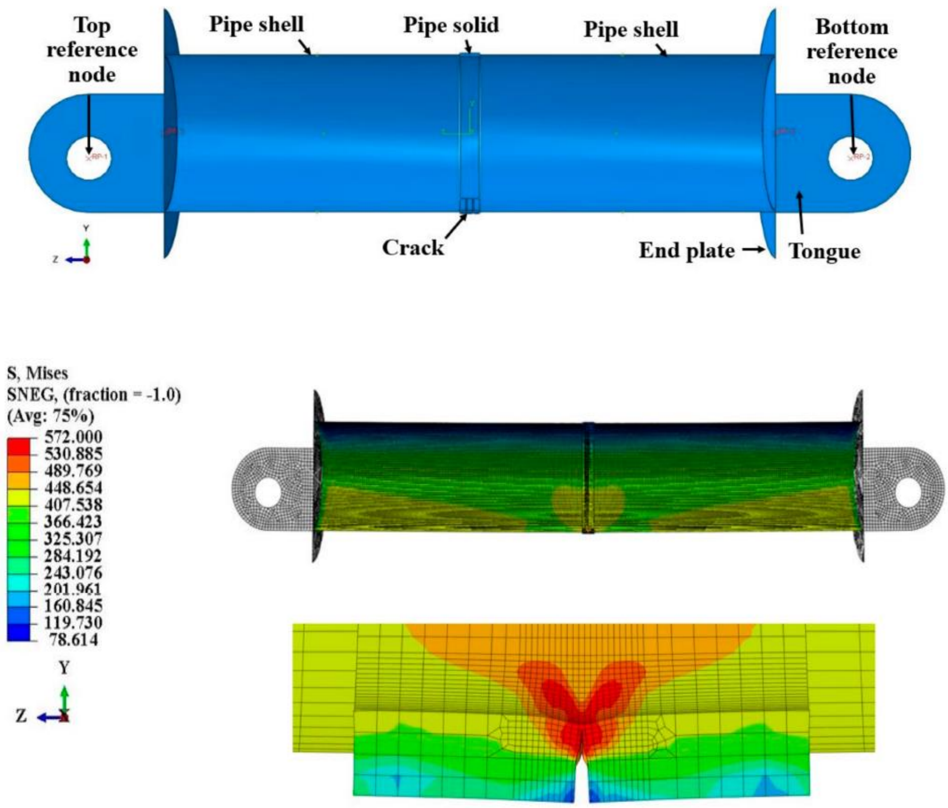

***Figure 6.** Assembled components of pipeline model and CMOD at the failure* (Elyasi et al., 2021)

In bending FSTs, stresses are spread non-uniformly throughout the circle, and it is typical to notch at the greatest strain site, which is the outer fibres on the tensile side (Darcis P. P. et al., 2009), (Darcis P. P. et al., 2010), (Demofonti, Mannucci, Hillenbrand & Harris, 2004). Bending tests are limited to one or two notches since there usually are only one or two welds per specimen with just one notch per weld. Four-point testing setup and an example of a silicon replica used to measure CMOD, CTOD, and Δa (crack extension) can be seen in *Figure 7* (Bastola et al., 2016).

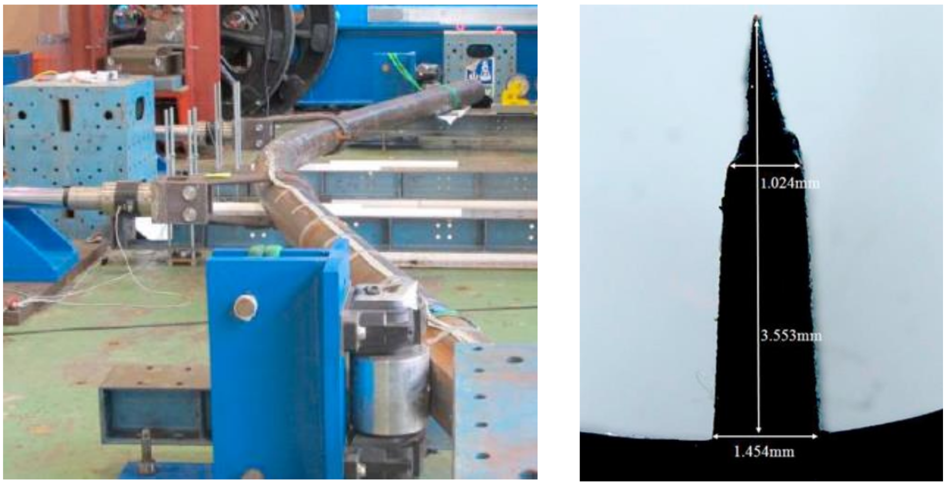

Figure 7. *Four-point testing setup and an example of measured notch dimensions* [19]

For project-related FSTs, sampling statistics might also be a source of worry. The advantage of many notches is significant insurance against the obstacles of full-scale testing, given the difficulty of notch placement, equipment dependability, and material variability. The potential of buckling is another reason why bending tests might be troublesome. The strain capacity of the notched region cannot be evaluated if a buckle (wrinkle) arises on the compression side of the specimen (a rather typical occurrence). When the specimen wrinkles, constant straining is no longer possible. Wrinkling can jeopardize FST goals if the goal is to evaluate the full strain capacity of the materials involved.

3.2. Pup selection and basic design

Preparation is much simpler if the FST is on the base pipe; tests using girth welds are more complex. Figure 1 shows a schematic of an FST specimen. This design consists of two girth welds that connect three pipe segments known as pups. To develop dependable techniques to accomplish the intended weld joint MA, weld strength overmatch, fault size, and flaw locations, design considerations, and quality controls are required (Bajcar, Cimerman, Širok & Ameršek, 2012), (Demofonti, Mannucci, Spinelly, Barsanti & Hillenbrand, 2002), (Di Vito et al., 2012), (Haagensen, Maddox & Macdonald, 2003).

In FSTs with girth welds, the number of girth welds (and hence pups) to include must be decided. The Authors have worked with various welds ranging from one to four (which means two to five pups). More girth welds provide the benefit of improving testing statistics. It permits additional artificial faults (basically notches) to be included, thereby turning a single FST into as many fracture tests as there are notches. More welds and notches have the disadvantage of increasing specimen complexity, preparation time, and the chance for mistakes, not to mention limiting the capacity of test machines. The Authors prefer the configuration depicted in *Figure 1* (two welds, three pups) based on their experience since it appears to maximize the conflicting elements.

Another factor to consider is the length of the pup. Pups must be long enough to avoid interfering with neighbouring welds and/or end caps. The authors recommend a minimum pup length of 1.5 to 2 outside diameters (OD) since this provides a total specimen length (many diameters) that more closely resembles an actual strain event in a pipeline. Pipe-soil interactions are beyond the scope of this work; suffice it to state that the length of a real pipeline exposed to the whole target demand is expected to be no less than a few diameters. As a result, FST specimens of at least a few diameters appear to be acceptable (Hertelé, Cosham & Roovers, 2016), (Kristoffersen, Haagensen & Rørvik, 2008), (Horn, Lotsberg & Orjaseater, 2018), (Hertelé, de Waele, Denys, Verstraete & van Wittenberghe, 2012).

It is possible that a decision on the pups' origins will be required. If there is just one pipe available to construct the specimen, the choice is clear. If numerous pipelines are present, however, the upstream source may change. If the test aims to make a model, the pups for each specimen should be cut immediately adjacent to each other and then welded back together in their original arrangement. This reduces variance in strain capacity across pups while maintaining the purpose of evaluating only one variable. If the FST is tied to a project, the original source is less important. The aim can be achieved as long as the puppy reflects the project material.

There have been instances where pups from different pipes were utilized, and test interpretation was challenging owing to differences in pipe qualities. In general, if combining puppies from separate pipes serves no benefit, this procedure should be avoided.

3.3. Prior material knowledge

Materials with which the designers have existing expertise should be used in the design and production of specimens for model building aims. This involves understanding the pipe longitudinal characteristics, weld strength, and weld toughness, at a minimum. Pre-testing can be quite beneficial; FST design and production should be guided by base metal tensile testing, welding trials, and measurement of weld characteristics. It is vital to remember that the FST specimen will have different material than any pre-tests, and there is a chance that there may be unanticipated alterations in the specimen (Lukács, Koncsik & Chován, 2021), (Lei et al., 2015), (Maddox, Speck & Razmjoo, 2008), (Maddox & Zhang, 2008).

Obtaining the correct degree of weld strength mismatch is one of the most essential parts of test specimen design and manufacturing. One of the most important factors affecting girth weld strain capacity is overmatch. Unexpected test findings have been linked to unintended overmatch variation, notably lower than desired overmatch.

Longitudinal tensile samples can be collected from rings cut right near to the pipe edges that will be bevelled for welding to assess pipe tensile qualities. If this is not possible, samples should at the very least be collected from the pipe that will supply the FST pups. Trial welding and all-weld metal testing are required without prior knowledge of weld metal qualities. Measuring weld tensile characteristics (which are used to calculate mismatch) may be difficult, thus planning ahead of time for pipe/weld geometry and tensile specimen shape is recommended.

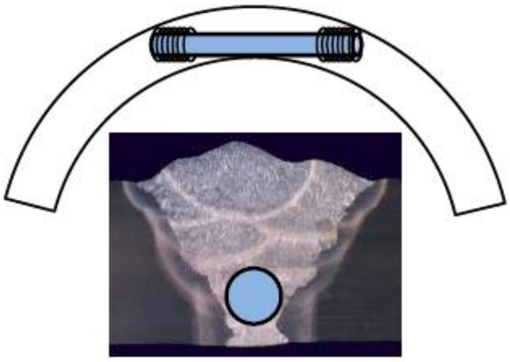

Figure 8. *Four-point testing setup and an example of measured notch dimensions*
(Fairchild, Shafrova, Tang, Crapps & Cheng, 2014)

The sample region must be weighed against the location of the FST notch. A round bar sample for small diameter pipe will be skewed toward the weld root [see *Figure 8* (Fairchild, Shafrova, Tang, Crapps & Cheng, 2014)], which may not reflect overall weld strength or be consistent with an FST notched from the OD.

If the pipe wall thickness approaches 25 mm, two round bar specimen sites in the weld cross section should be considered, one higher and one lower. A rectangular cross section specimen is an alternative to the round bar geometry. This specimen has been recommended for narrow groove welds, but because the design samples a larger quantity of weld metal than round bars, it has merit regardless of bevel form (Mahdavi, Kenny, Phillips & Popescu, 2013), (Spinelli & Prandi, 2012), (Netto, Botto, & Lourenço, 2008).

3.4. Notches

3.4.1. Internal vs. external notches

FST notches can be cut into the pipe's inside diameter (ID) or outside diameter (OD). A variety of factors influence this decision. Because of access issues, ID notches are impracticable for pipes with a diameter of less than DN450-DN500 (18–20"). It is technically viable to apply ID notches if the FST is significant enough for access, but the test will be pressured; nevertheless, the inside environment (water) considerably increases test complexity and restricts the durability of notch instrumentation. The chance of losing ID signals during the test is high.

Several authors have shown that real pipeline failures occur more frequently at the root than at the cap, owing to the higher risk of root faults. FSTs from the ID are more likely to be notched because of this reality (Lukács, Nagy, Harmati, Koritárné & Kuzsella, 2012), (da Costa Mattos et al., 2016), (Örjasaeter, Hauge, Bärs & Kvaale, 2004), (Meiwes, Höhler, Erdelen-Peppler & Brauer, 2014), (Ørjasæter, Knagenhjelm & Haagensen, 2008). However, in the presence of superimposed bending and the resulting bending stresses, external notches on the tensioned side can significantly reduce the lifetime of a real pipeline session. Such stresses can be caused by several factors, such as construction, ground movements (Kristoffersen, Haagensen & Rørvik, 2008), (Rofooei, Jalali, Attari & Alavi, 2012), and climatic changes.

3.4.2. Cracks vs. notches

Large-scale fracture mechanics tests are essentially what FSTs are. Because of the influence of defect tip acuity and the possibility for brittle fracture in structural steels and their welded joints, fracture tests have traditionally been done with fatigue precracks (ISO 12135, 2021), (ISO 15653, 2018), (ASTM E647-15e1, 2015). Precracks, on the other hand, are extremely difficult to implement in full-scale pipe specimens.

FSTs for SBD are currently done with notches. SBD circumstances necessitate careful consideration of design elements and material integrity. Both the pipe and the weld materials must be ductile, and a comprehensive materials testing procedure must show this. Other tests (Charpy impact, CTOD) can be used to confirm ductile behaviour in more traditional methods. After that, FSTs can be performed using sharp notches rather than precracks because both will operate similarly in a ductile material. The results of SENT testing have corroborated this. The breadth of the notch should be kept to roughly 0.2 mm.

Low-temperature testing may be relevant because of the brittle fracture worry; nevertheless, for model construction FSTs, room-temperature testing can be justified. This is because SBD models are only applicable to ductile behaviour by definition. If the test materials are suspected of not being ductile at room temperature, Charpy and/or CTOD testing should be conducted to guarantee that the test will not be hampered by brittle behaviour. If the testing is for a project, the test temperature may be determined by the application’s severity. If the service temperature is expected to be very low (below –10 °C), it could be careful to execute at least some investigations at that temperature.

3.4.3. The quantity of notches

Because it enhances test statistics (number of investigated notches), it is preferable to include as many notches as feasible in an FST. Too many notches, on the other hand, may produce interaction between neighbouring notches, jeopardizing the test findings [unless flaw interaction is the goal (Lukács, Koncsik & Chován, 2022)]. To investigate interaction effects and improve notch spacing, FEA can be employed.

For pipe diameters smaller than roughly DN700 (30"), two notches spaced 180° apart are usually utilized. For pipes ranging from DN700 (30") to DN1150 (42"), three evenly spaced notches can be utilized. Four notches might be considered for bigger pipes. The flexibility to adjust notches in the last phases of specimen preparation and/or to obtain the desired level of MA must be balanced with an aggressive notch number strategy. After the weld MA and non-destructive examination (NDE) results are known, the notch placements may be finalized. The target MA may be only found in a few places. To reach the right MA or prevent weld defects, it may be required to shift notches a substantial distance from the initial plan.

3.4.4. Misalignment in welded joints

One of the most critical factors influencing strain capacity is weld joint MA. By raising MA from zero to a few millimetres, strain capacity can be greatly decreasing (Lotsberg, 2009), (Hobbacher, 2008), (Qingshan, Yi-han, Bin, & Hanchen, 2010), (Chaudhari & Belkar, 2014), (Weeks, McColskey, Richards, Wang & Quintana, 2014). It has been established that the pipe offset approach may be utilized to construct MA in an FST. Once the weld joint has been constructed, it is recommended that MA be measured at regular intervals around the perimeter and that this information be utilized to guide final notch placement, together with weld NDT data.

MA makes determining fault depth difficult. A schematic of probable HAZ notch placements in relation to a misaligned weld is shown in *Figure 9*. Despite the fact that these notches all enter the material to the same depth, the FST notch depth must be defined differently. The notch location should be consistent with the model if the FST's objective is to construct models. In the case of HAZ notches, the notch is often placed on the "lower" side of the weld, whether for model construction or project work. When compared to the "higher" HAZ position, this position is more cautious since it generates a smaller cross section between the notch tip and the weld root.

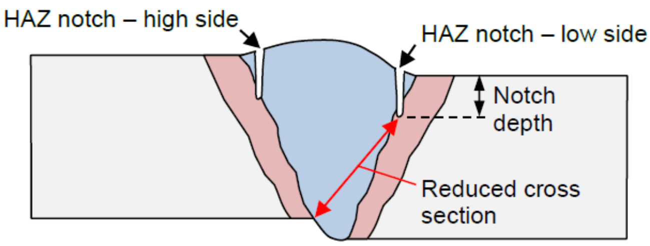

Figure 9. *Possible HAZ notch positions when MA is present*
(Fairchild, Crapps, Cheng, Tang, & Shafrova, 2016)

Calculation changes will be required if the notch position is at the weld centreline and the notch depth is referred to the low side of the weld (see *Figure 10*). The notch penetration depth is derived by multiplying the notch depth by the height of the notch entrance point X. The cap is frequently ground to assist clip gage installation, thus the weld cap in *Figure 10* is rather flat to approximate this. The height of the entrance point X in this example is roughly half of the MA. The actual cap height may differ from that depicted in *Figure 10*, requiring the designers to make the required changes.

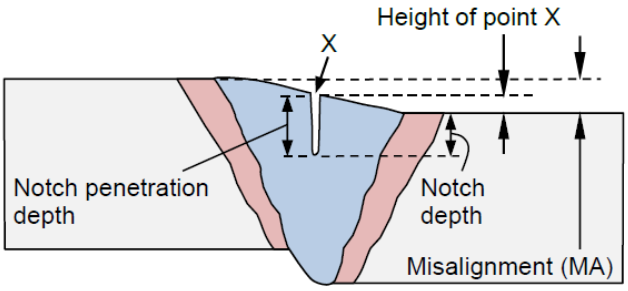

Figure 10. *Weld centreline notch position showing additional considerations when MA is present*
(Fairchild, Crapps, Cheng, Tang & Shafrova, 2016)

4. CONCLUSIONS

From the detailed review and processing of the references, the following main conclusions can be drawn.

- Model construction and project work are the two most common motivations for FSTs. Depending on the FST's goal, the specimen design and manufacturing, test process, and data analysis may change.
- Performing a single FST is very expensive and can be taken months. The investment necessitates meticulous pipe and weld selection, specimen construction, instrumentation, and analysis of the findings. Material variances should be kept to a bare minimum since they can jeopardize an FST.
- Misalignment makes notch insertion more complex, therefore prior planning and precise measurement are all essential. In addition, to find the notches near a (hidden) fusion line, HAZ notching necessitates using registry lines and companion cross sections.
- In an FST, the material qualities are represented by companion pipe/welds. Variations in companion materials and the FST should be avoided at all costs since they can skew the findings.
- Pipes that are utilized for SBD-related FSTs should be aged.
- Well-defined test shutdown criteria are required to get the most out of an FST.
- A comprehensive metallurgical inspection should be complemented with a rigorous assessment of all instrumentation data to obtain a complete knowledge of specimen performance. Fractography becomes an essential part of the post-test assessment if the FST breaks. To assess the relevance of

cleavage on an FST fracture surface, it should be evaluated. The presence of cleavage does not always imply that the materials are inappropriate for SBD.

- FSTs are a must-have tool for ensuring the safety of SBD pipelines. FSTs should be deemed necessary until the industry has gained considerable expertise with these pipelines and/or improved modelling (prediction) accuracy.

5. CONSEQUENCES OF DESIGNING AND EXECUTING OWN INVESTIGATIONS

The following conclusions can be drawn for designing and implementing our own full-scale investigations.

- When designing the tests, all available information and data on the pipeline sections to be tested, the actual operating conditions, the test possibilities, and the limitations should be used.
- If necessary, additional mechanical tests and microstructural investigations shall be carried out to ensure high reliability and reproducibility of the test pipeline sections. Furthermore, non-destructive examinations of girth welds are practical and necessary in connection with the essential phases of the full-scale tests (e.g. before the tests, after the fatigue tests).
- The tested pipeline sections should be constructed from the same material quality. In cases where this is not possible, special attention should be paid to differences in the properties of the pipe sections and their effects on the tested girth welds.
- The longitudinal size of the individual pipe sections used for the assembly of the tested pipeline sections should preferably exceed twice the outer diameter.
- The use of three-segment tested pipeline sections with two tested girth welds is appropriate for four-point bending tests. A three-point bending test is preferable if only one girth weld is to be tested.
- In order to model actual operating conditions as accurately as possible, applying an external (bending) load in addition to the internal (cyclic) pressure is desirable. In such cases, placing the tested girth weld in the middle of the investigated pipeline section is advisable. This will result in the highest bending stress (three-point bending) and eliminate errors due to asymmetry (four-point bending).
- Before complex load tests, it is also advisable to investigate a pipeline section that has not been subjected to cyclic loading (burst test), furthermore a pipeline section that has not been subjected to additional loading (fatigue test followed by burst test). These investigations provide a basis for comparison with the complex loaded investigations.
- In order to model the defects of the girth welds, it is advisable to use notches. In the case of simple loads, the location of the notches along the circumference is indifferent, but in the case of complex loads, the locations with the highest stress should be prioritized.

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