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Review Article

A review on hydrogen embrittlement and risk-based inspection of hydrogen technologies

Alessandro Campari [a,*], *Federico Ustolin* [a], *Antonio Alvaro* [b], *Nicola Paltrinieri* [a]

[a] *Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Richard Birkelands vei 2b, Trondheim, 7034, Norway*

[b] *SINTEF Industry, SINTEF, Richard Birkelands vei 2b, Trondheim, 7034, Norway*

HIGHLIGHTS

- The occurrence of hydrogen-induced material failures requires safety enhancements.
- Hydrogen embrittlement relies on a synergistic interplay of several factors.
- Tailored inspection activities could aid to monitor equipment exposed to hydrogen.
- RBI approaches are not used for planning inspections of hydrogen technologies.
- Material science and safety are often considered two separated research fields.

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ABSTRACT

Hydrogen could gradually replace fossil fuels, mitigating the human impact on the environment. However, equipment exposed to hydrogen is subjected to damaging effects due to H_2 absorption and permeation through metals. Hence, inspection activities are necessary to preserve the physical integrity of the containment systems, and the risk-based (RBI) methodology is considered the most beneficial approach. This review aims to provide relevant information regarding hydrogen embrittlement, its effect on materials' properties, and the synergistic interplay of the factors influencing its occurrence. Moreover, an overview of predictive maintenance strategies is presented, focusing on the RBI methodology. A systematic review was carried out to identify examples of the application of RBI to equipment exposed to hydrogenated environments and to identify the most active research groups. In conclusion, a significant lack of knowledge has been highlighted, along with difficulties in applying the RBI methodology for equipment operating in a pure hydrogen environment.

* *Corresponding author*.
E-mail address: alessandro.campari@ntnu.no (A. Campari).

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Contents

Introduction

Hydrogen has been recently indicated by the European Commission and the Norwegian Ministry of Petroleum and Energy as a promising fuel to reduce greenhouse gas emissions [1,2]. The growing interest in the widespread rollout of this energy carrier rests on two factors: hydrogen can be used with very limited direct pollutant emissions, and it can be produced from various low-carbon sources by steam reforming as well as from water by electrolysis [3,4]. The importance of hydrogen in the global energy scenario is reflected by its rising share in the total final energy consumption: hydrogen accounted for less than 0.1% in 2020 [5], but it is expected to reach 2% by 2030 and 10% in 2050 [6].

Despite the advantage of being potentially clean and renewable, there are serious safety concerns associated with hydrogen properties. Along with hydrogen flammability and explosivity, the capability of permeating and embrittling metallic materials are critical safety issues associated with hydrogen handling and storage [7]. Hydrogen can be absorbed by most metals and alloys, and its accumulation in the proximity of internal defects (e.g., vacancies, grain boundaries, dislocations, precipitates, and inclusions) represents a serious concern for iron, steels, nickel and titanium-based alloys, and many other materials normally employed for industrial applications [7,8]. The hydrogen-induced degradation of mechanical properties of metallic materials was first-time observed by Johnson in 1874 [9] and validated by Reynolds one year later [10]. Thereafter, the mechanisms responsible for hydrogen-related damages have been widely researched. Despite the variety of theories that have been proposed to explain the complex interaction between metallic materials and hydrogen, the underlying mechanisms are still being discussed [11–13]. Although the hydrogen-induced degradation of metals has been extensively investigated over the years, hydrogen embrittlement (HE) is still responsible for many industrial failures and associated catastrophic releases of hazardous substances in the environment [14–17]. Components for storing and transporting compressed gaseous hydrogen (CGH_2) are exposed to hydrogenated working environments at high-pressures and near-ambient temperatures. They can be subjected to elevated stresses and exposed to cyclic loads, resulting from the pressure fluctuations during normal operations (e.g., in pipeline systems, cylinders, and tanks). In addition, most of these equipment items have not been specifically designed for hydrogen service and therefore, the construction materials can be highly degraded by H_2. Hence, inspection and maintenance activities must be performed to preserve the physical integrity and fitness-for-service of components exposed to hydrogen environments. Over the last decades, maintenance strategy has undergone radical changes, moving from corrective to predictive approaches. In particular, the risk-based methodology is considered the most beneficial strategy for inspection and maintenance planning. This approach has been largely adopted in the chemical and petrochemical industries, but its application to hydrogen technologies is still challenging.

This review aims to answer the following research questions.

- How does hydrogen embrittlement affect equipment for hydrogen handling and storage?
- How to plan inspection and maintenance towards hydrogen-induced material degradation of equipment for CGH_2 transport and storage?

The increasing interest of the scientific community in these topics is confirmed by some ongoing research projects, such as the European H_2 CoopStorage [18], the Norwegian SH_2IFT-2 [19], and the Euro-Japanese project SUSHy [20]. Several review papers regarding the hydrogen embrittlement effects on various steels (e.g., pipeline steels [21–25], martensitic high-strength steels [26,27], austenitic stainless steels [28,29], medium and high-Mn steels [30,31]) were recently published. Moreover, the techniques to prevent hydrogen embrittlement were investigated by several researchers [32–34], which focused on the influence of microstructural features [35–37], the utilization of gaseous inhibitors [38–40], or the adoption of surface coatings [41–43]. Nevertheless, a thorough review regarding the inspection and maintenance of hydrogen technologies and the techniques to detect hydrogen-induced damages is still missing.

This work adopts a hybrid approach: a systematic review (SR) was conducted sequentially to a narrative review (NR). This innovative methodology is capable not only to answer the abovementioned research questions but also to highlight the main trends and pinpoint the most active groups in this research field. The method adopted is extensively described in the Methodology section. In addition, the most relevant information about the HE effects and the influencing factors for materials' susceptibility is presented in the Hydrogen embrittlement section. The Methodologies for inspection and maintenance planning section comprehends both the traditional approaches and the RBI methodology. The main findings of the SR are presented with the aid of graphs and tables and extensively discussed in the Systematic review and Discussion sections, respectively. A summary of the main findings and suggestions for future research are provided in the Conclusion.

Methodology

The methodology for this study is based on both a narrative and a systematic review. The former aims at identifying and summarizing results of previous research, avoiding duplicates, and looking for new study fields to be investigated [44]. In contrast, the ultimate objective of the latter is to formulate a clearly defined research question and provide a quantitative and qualitative analysis of the state of the art, potentially followed by a meta-analysis [45]. A systematic review has inclusion criteria explicit and reproducible and is quantitative, comprehensive, and structured. This paper follows the guidelines provided by Xiao and Watson [46] and applies the methodology of the PRISMA Statement [47] to transparently conduct a systematic review. The process for carrying out this review can be divided into five phases.

1. Identifying the research area and carrying out a narrative review
2. Identifying specific queries
3. Identifying, screening, and selecting relevant studies
4. Mapping and presenting the data
5. Summarizing and reporting the findings

Fig. 1 shows how this hybrid methodology was applied to the present study.

The focus of the review is primarily placed on hydrogen embrittlement and its implications in the inspection and maintenance of equipment operating in pure hydrogen environments. A brief overview of various inspection planning approaches is provided, focusing on the RBI methodology. Although the major bibliographic sources were represented by journal papers and conference proceedings, grey literature (e.g., reports, standards, recommended practices, and government documents) was also included, where relevant. Subsequently, the queries of the systematic review were defined based on the results of the narrative review.

The SR was completed on November 20, 2022. The data were collected from the Web of Science Core Collection (WoS CC) database [48]. The first keyword of each query was related to hydrogen embrittlement or generically to hydrogen, while the second was associated with risk-based inspection and maintenance, or to inspection and maintenance in general. In addition, several filters were applied for rapid screening of the records. For the sake of clarity, all the queries and filters selected are collected in Table 1.

After identifying the records from the database, they were screened based on title, keywords, and abstract. Then, a more thorough assessment for eligibility was carried out by reading the full-text papers. In addition, several other records were selected through forward-backwards searches. Finally, keywords co-occurrence maps, co-authorship networks, and countries networks were created through VOSviewer [49], a software tool with text mining capability specifically designed to perform bibliometric analyses.

A hybrid methodology is a valuable tool to perform an objective, transparent, and reproducible analysis of the state of the art and to enhance the quality of the literature review. This approach allows for reducing the inevitable bias of narrative literature reviews, even if it cannot be completely avoided since the records gathered from WoS CC must be manually screened and assessed for eligibility. In addition, rigorous statistical methods and automatic pattern recognition allow for describing and evaluating the state of the art and predicting the future trends of this research field. The qualitative and quantitative analyses turn out to be essential to have a descriptive overview of the state of the art and to highlight the most active institutions and groups and their connections.

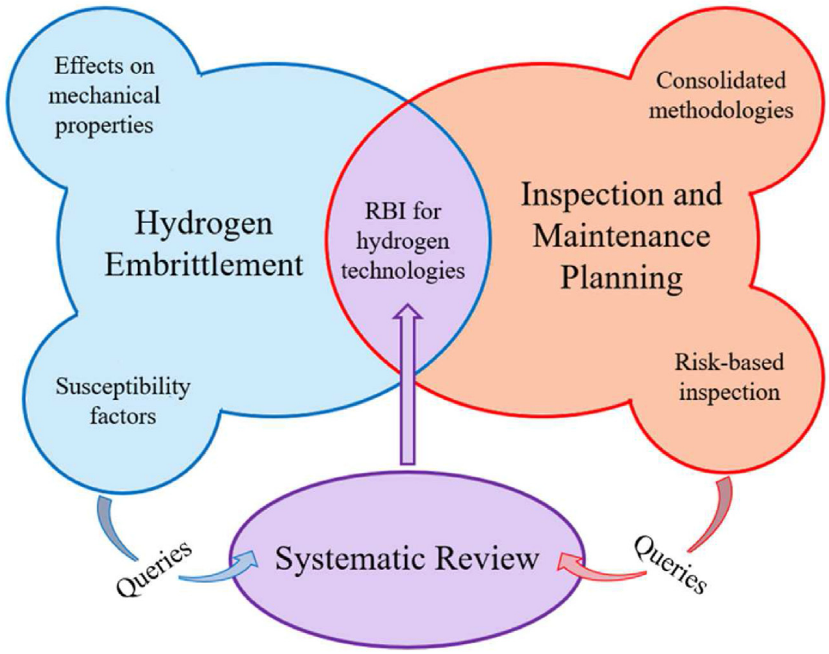

Fig. 1 – Schematic methodology of this study.

Hydrogen embrittlement

Hydrogen embrittlement is a degradation process resulting in the reduction of materials' mechanical properties due to the interaction with hydrogen atoms from the component's working environment. In equipment exposed to hydrogenated environments, hydrogen is dissociated and absorbed in the material. Absorbed atoms diffuse through the metal's bulk, preferentially toward high triaxial stress regions, and locally affect the material resistance to internal stress or external load [13]. Despite being a long-known phenomenon, HE is still responsible for unpredictable failures in many applications, such as storage tanks, fasteners, process reactors, pipelines, fuel cell vehicles, and aircraft components [14,17]. This section focuses on the HE theory, its effects on tensile and fracture resistance properties, and the hydrogen-enhanced fatigue crack growth rate (HEFCGR). In addition, the main susceptibility factors and their synergistic interaction are discussed.

Hydrogen embrittlement theory

Most of the equipment for H_2 handling, transport, and storage is exposed to high-pressure hydrogenated environments and can be subjected to monotonic and cyclic loading. In addition, hydrogen can be absorbed into the metal during the component's fabrication or through cathodic protection (in the case of subsea pipelines) and corrosion processes. This section presents concisely the mechanism of hydrogen uptake into metals in compressed gaseous atmospheres.

The size of the H_2 molecule is too large to diffuse through metals. Thus, hydrogen is dissociated into atoms on the metal surface and enters the materials in two distinct steps, known as adsorption and absorption. The former is based on the hydrogen gas-metal interaction and comprehends the

Table 1 – Queries and filters selected in Web of Science Core Collection for the systematic review.

Type	Option selected
Queries[a]	“hydrogen* embrittlement*” “inspection” OR “hydrogen* embrittlement*” “maintenance” OR “hydrogen* damage*” “inspection” OR “hydrogen* damage*” “maintenance” OR “hydrogen*” “risk-based inspection” OR “hydrogen*” “risk-based maintenance”
Analysis Field	Topic
Document type	Articles, Review Articles, Conference Proceedings
Language	English
Countries	Global
Period examined	Not applied

[a] The quotation mark allows to search for an exact word or phrase, whereas the asterisk can be used to look also for similar words.

mechanisms of physisorption and chemisorption, which can be distinguished in terms of bonding energy (weak van der Waals forces for physisorption and covalent bonding for chemisorption). Hydrogen adsorption on the metal surface is based on the following reversible reaction [50]:

$$H_2 + 2M \leftrightarrow 2MH_{ads} \tag{1}$$

The Sievert's law states that hydrogen concentration in metals is proportional to the hydrogen partial pressure under thermodynamic equilibrium conditions:

$$C_H = K \cdot \sqrt{p_{H_2}} \tag{2}$$

where C_H indicates the concentration of dissolved hydrogen, K is the equilibrium constant, and p_{H_2} is the hydrogen partial pressure. The concentration of dissolved H depends on the temperature, according to the Arrhenius law:

$$C_H = C_0 \sqrt{p_{H_2}} \cdot e^{-\left({}^{\Delta H_s}/_{RT}\right)} \tag{3}$$

where C_0 represents the pre-exponential factor, ΔH_s the dissociation enthalpy of the hydrogen molecule, R is the gas constant, and T the temperature [51].

After the adsorption on the metal surface, hydrogen can either recombine in molecular form and release gaseous H_2 in the environment or recombine in a surface-subsurface absorption reaction and diffuse through the bulk material. These competing mechanisms are described by the following reactions [50]:

$$MH_{ads} + MH_{ads} \rightarrow 2M + H_2 \tag{4}$$

$$MH_{ads} + M \leftrightarrow M + MH_{abs} \tag{5}$$

Once absorbed into the metal, hydrogen atoms can occupy interstitial sites and jump from one site to another, moving through the material. The atomic radius of hydrogen (i.e., $5.3 \cdot 10^{-11}$ m) is similar to the size of the interstitial sites in the body-centered cubic (bcc) and face-centered cubic (fcc) structures, and this allows for elevated H atoms' mobility [52]. Temperature, chemical composition, and microstructure strongly influence the diffusivity. Hydrogen solubility is lower in bcc materials (e.g., ferritic steels) than in fcc (e.g., austenitic steels). In fact, despite the higher number of interstitial sites in bcc structures, their size is comparatively smaller. The hydrogen diffusion depends on the concentration gradient and is described by Fick's first law [53]:

$$J_H = -D_H \cdot \nabla C_H \tag{6}$$

where J_H represents the hydrogen flux and D_H is the diffusivity.

In a theoretically perfect lattice, hydrogen should distribute homogeneously in the crystal structure. Despite this, real materials have imperfections and microstructural features that act as trapping sites, i.e., potential gaps where hydrogen atoms get trapped [54]. These sites can be divided into reversible and irreversible traps, depending on their binding energy. H atoms can escape from vacancies, dislocations, and grain boundaries thanks to the low binding energy of these microstructural features. On the other hand, higher activation energy is necessary to release hydrogen atoms from irreversible traps. Hence, H atoms can either diffuse from one interstitial site to another or be trapped within the material [55–57].

The mechanisms through which hydrogen is adsorbed, absorbed, transported, and trapped are generally well-accepted. In contrast, the physical mechanism responsible for the hydrogen embrittlement effect is still debated in the scientific community. The most accepted opinion is that the degradation is caused by the interaction of several mechanisms, such as Hydrogen-Enhanced Decohesion (HEDE) and Hydrogen-Enhanced Localized Plasticity (HELP) [58]. The HEDE theory suggests that embrittlement is caused by a local reduction of cohesive strength in the metal lattice, thus provoking the separation of cleavage planes or grain boundaries under lower stress levels. In other words, the atoms are separated when the applied stress exceeds the local cohesive strength in the crack tip; the interatomic bonds are weakened by the presence of hydrogen in the lattice, thus resulting in atoms' separation [59]. On the other hand, the HELP mechanism states that H atoms enhance dislocation mobility by causing a local reduction in shear stress. Hydrogen transport, accelerated by dislocation movement, causes an increase in H concentration near the crack tip. The accumulation of hydrogen around dislocations enhances the local strain, which disrupts the crystal structure. If the local hydrogen concentration is sufficient, the deformation can lead to a macroscopic brittle fracture [60,61].

Effects on mechanical properties

Industrial equipment exposed to high-pressure hydrogen gas may operate under various loading conditions. Concerning the HE phenomenon, the effect on mechanical properties can be roughly divided into two categories: quasi-static and dynamic. The former indicates a constant or slowly varying load, which allows for a general hydrogen distribution equilibrium; it is often relevant for components exposed to high gas pressure. On the other hand, the latter is associated with dynamic components (e.g., compressors), vibrations in static equipment, or fluctuations in gas pressure [62]. Due to the time-related nature of the HE phenomenon, the materials' susceptibility is often investigated through tests performed in quasi-static conditions. Tensile properties, fracture resistance properties, and fatigue crack growth rate (FCGR) under cyclic loading need to be quantified in a relevant hydrogenated operating environment in order to assess the performance and integrity of components commonly used in the hydrogen value chain [22].

Tensile properties

Slow strain rate tests (SSRTs) are normally used to test the materials' tensile properties [63]. Hydrogen-induced degradation often manifests itself as a ductility loss and can be expressed as the change in reduced areas after a tensile test obtained in the hydrogenated environment and in a reference environment [64–66]. This is usually quantified through the Embrittlement Index [67]:

$$EI = \frac{RA_{ref} - RA_{H_2}}{RA_{ref}} \cdot 100 = \frac{[(A_i - A_f)/A_i]_{ref} - [(A_i - A_f)/A_i]_{H_2}}{[(A_i - A_f)/A_i]_{ref}} \cdot 100 \quad (7)$$

where RA_{ref} and RA_{H_2} are the reduced area at fracture in a reference environment (air or inert gas) and hydrogen, respectively, and A_i and A_f represent the initial and the final fracture areas, respectively. High values of EI are associated with the high HE susceptibility of the tested material.

While elongation and reduction of area at fracture are strongly affected by the hydrogen-metal interaction, elastic properties, yield strength (YS) and ultimate tensile strength (UTS) are often barely modified [68–71]. Generally, metals with higher strength feature stronger susceptibility to hydrogen degradation. San Marchi et al. [64] tested the tensile properties of a wide range of carbon and low-alloy steels in gaseous hydrogen environments (at 6.9 and 69 MPa); the results show that the loss of RA for smooth specimens ranges from 20% to up to 50%, compared with values measured in air. Other studies confirmed similar findings for X52 and X65 pipeline steels [45,49]. Fig. 2 shows the fracture surfaces of X65 specimens with and without hydrogen charging.

The presence of geometrical imperfections or notches, which act as stress concentrators, can significantly increase the material susceptibility to HE. As mentioned earlier, this enhanced sensitivity is associated with the inherent presence of a region ahead of the notch with higher triaxial stress and a high strain zone at the notch root, resulting in higher hydrogen accumulation in these areas and greater localized embrittlement [50,51]. Notched specimens present significant losses in the reduced area and limited changes in yield and tensile strength. In this case, the RA in hydrogen gas ranges from 5 to 9%, while the reduced area loss is up to 80%. Aside from the quantitative measurement of the hydrogen effect on tensile properties, SSRT can also be used as a screening method to select materials for hydrogen service [73,74]. To rigorously assess the reliability of steels exposed to hydrogen gas, tests on cracked specimens, both under monotonic and cyclic loading, are required [54]. Table 2 summarizes the HE susceptibility of several steels, based on the EI measured at 24 °C and 69 MPa hydrogen gas.

Fracture resistance properties

Fracture resistance properties are quantified by fracture toughness tests, performed on a pre-cracked specimen, which is subjected to monotonically increasing load, whilst the crack mouth opening displacement (CMOD) is monitored. Fracture toughness is typically expressed in terms of plane strain fracture toughness K_{IC} (MPa·m$^{1/2}$) or elastic-plastic fracture

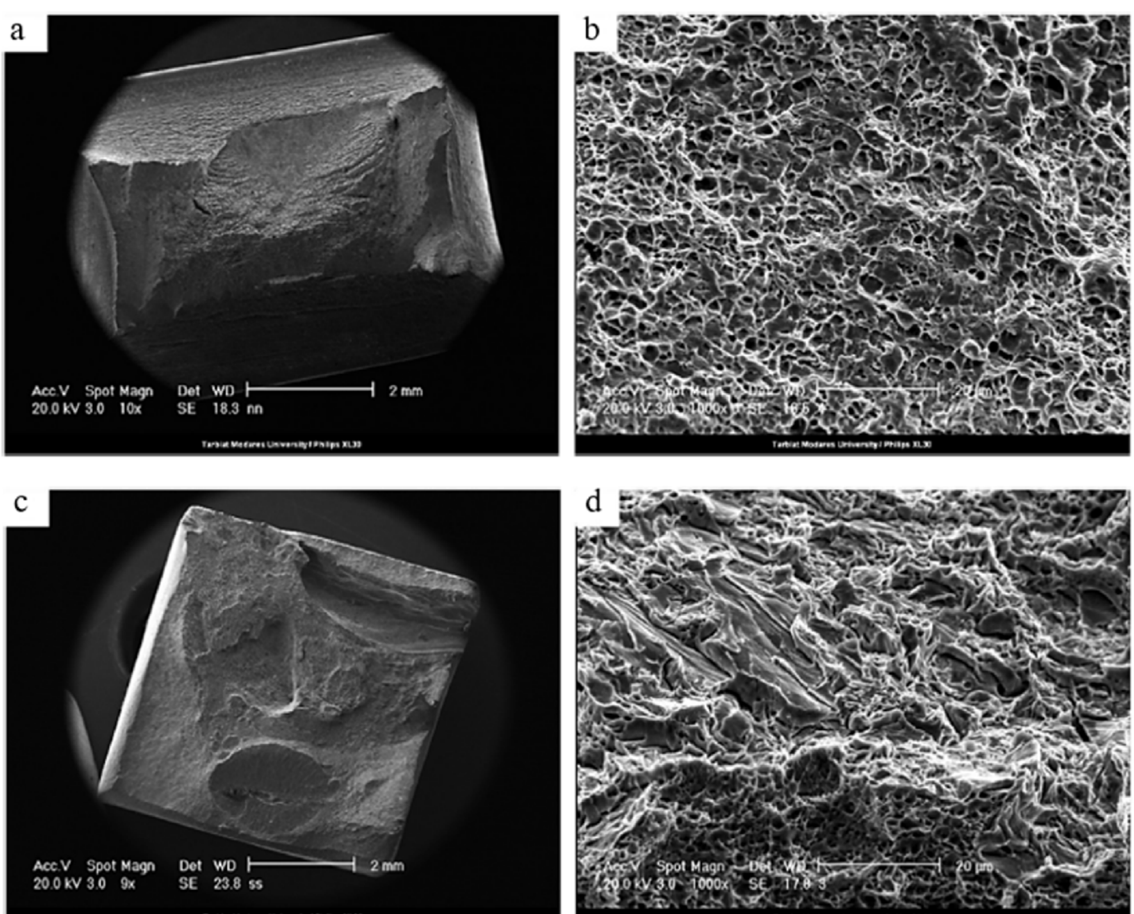

Fig. 2 – SEM magnified fracture surface of an X65 steel weld uncharged (a) macroscopic and (b) microscopic, and hydrogen-charged (c) macroscopic and (d) microscopic [72].

Table 2 – Hydrogen embrittlement susceptibility of selected steels tested at 24 °C under 69 MPa hydrogen gas (adapted from Ref. [75]).

HE susceptibility	Notes	EI	Austenitic steels	Ferritic steels	Martensitic steels
Negligible	Useable in pressurized hydrogen environments	0.00–0.03	A286, 216, 316, 22-13-5		
Small	Useable in hydrogen environments under controlled temperature and pressure	0.04–0.10	309S, 310, 347, 18-3-Mn	X60, X65, X70,	
High	Useable for limited hydrogen applications with fracture and fatigue crack growth analysis	0.11–0.30	Tenelon, A302B, 304L, 304 N, 305, 308L, 321, 21-6-9 + 0.1 N, 21-6-9 + 0.3 N	A106-Gr. B, A372, A515-Gr. 70, A516, A517-F, A533B, HY-80, HY-100, Iron, X42, X52, 1020, C1025	
Severe	Not recommended for hydrogen applications	0.31–0.50	18-2-12, 18-18 Plus, 18-2-Mn	A212-61T, X100, 430F, 1080	
Extreme	Not useable for hydrogen applications at any temperature and pressure	0.51–1.00	CG-27	1042, 4140, 4340	AerMet 100, D6AC, H11, Fe–9Ni–4Co-0.20C, 410, 440A, 440C, 17–4 PH, 17–7 PH, 18Ni-250 Maraging

toughness J_{IC} (kJ/m^2) [76]. The elastic-plastic J-integral method is used to measure the fracture toughness of metals for engineering applications, according to BS 7448–4 [77], ASTM E1820 [78], and ISO 12135 [79].

Fracture resistance properties may be highly decreased when a material is exposed to hydrogen gas, especially in weldments, causing brittleness in otherwise ductile materials [80–82]. If not carefully accounted for, this toughness decrease can represent a serious concern in the design of steel components, where small, undetected cracks may be always present. Robinson and Stoltz tested an A516 Grade 70 steel over a hydrogen pressure range of 3.45–34.5 MPa and proved how the detrimental effect of hydrogen was significant and proportional to its partial pressure [83]. Further studies confirmed the pressure dependence of the fracture toughness reduction [84,85], as shown in Fig. 3.

San Marchi and Somerday found that the fracture toughness of pipeline steels in a hydrogen environment can be from 48% to 60% of that measured in air, but its value remains high enough for most engineering applications (greater than 100 MPa·m$^{1/2}$ for steel grades up to X70) [64]. Nonetheless, the hydrogen-induced detriment of fracture toughness depends also on the presence of micro-alloying elements and specific microstructural features [86]. The dependence on the material microstructure is even more pronounced for the crack growth resistance (expressed as dJ/da). The values of dJ/da for hydrogen-charged carbon steels can be up to 90% lower than those measured in inert environments [64]. In other terms, the presence of hydrogen not only lowers the stress required to propagate a crack but also decreases the resistance for further crack propagation once this critical stress level has been reached.

Fatigue crack growth rate

Hydrogen can negatively influence the metals' resistance to fatigue crack growth rate under cyclic loads resulting from pressure fluctuations in equipment for hydrogen transport and storage or from the movement of rotating components

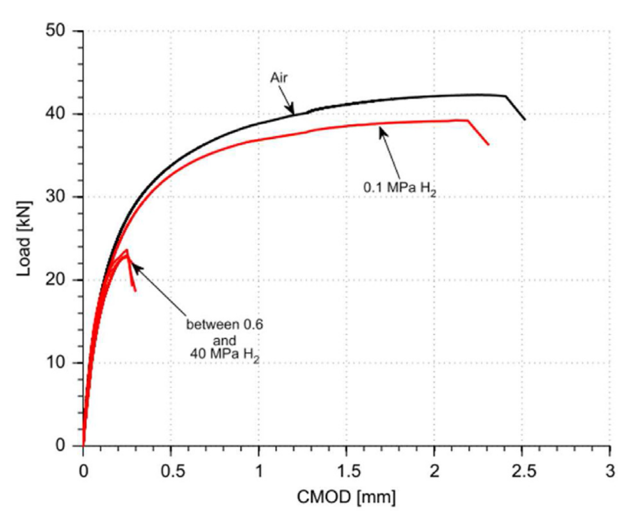

Fig. 3 – CMOD - Load curves for an X70 weld simulated HAZ at different hydrogen gas pressures [85].

[28,65]. The FCGR test method quantifies the rate of a crack in terms of crack advance per load cycle and is performed on pre-cracked specimens [87,88]. Minor imperfections, especially in welded areas and heat-affected zones (HAZs), can act as crack initiation sites in real components [66,67]. The per-cycle variation of the crack length da/dN (mm/cycle) is reported as a function of the stress intensity range ΔK ($MPa \cdot m^{-1/2}$). Most metallic materials display three different stages of crack propagation in hydrogen environments. The first stage, known as the threshold domain, reports the crack growth at low ΔK, where the fatigue crack seems to be latent below the threshold ΔK_{th}. In this regime, the data obtained in hydrogen often converge with those in the reference environment. Nonetheless, the test parameters can have significant spurious effects on the recorded ΔK_{th}. The second stage, the Paris domain, is an intermediate zone where it is possible to apply a continuum approach. The crack growth is described by the Paris equation [89]:

$$da / dN = A(\Delta K)^m \tag{8}$$

where A and m are both material constants. In this region, tests in hydrogen show a sharp increase in FCGR compared to tests conducted in the air. The magnitude of the acceleration is strongly dependent on the material system and can reach up to three orders of magnitude for high-strength steels [90,91]. Finally, the third stage, the unstable regime, manifests an accelerated crack growth, which is reached when K_{max} approaches the critical stress intensity K_{IC}. The slope of the FCGR in hydrogen is comparable to that measured in the air since the effect of hydrogen has already reached its maximum, and no further acceleration can be observed [90]. Fig. 4 shows the increased FCGR of an X80 pipeline steel tested in hydrogen compared to that tested in the air.

The available results in the literature indicate that, when tested without a pre-existing crack, the material's fatigue life seems to be slightly influenced by the presence of hydrogen as far as the stress ranges are around the material fatigue limit, i.e., in the high-cycle fatigue domain [93]. Nonetheless, variations due to the hydrogen-induced fatigue crack growth acceleration are recorded in the low-cycle fatigue domain. Hydrogen can increase the FCGR by one or two orders of magnitude if the stress intensity range is higher than ΔK_{th} [64,92,94–102]. The value of ΔK_{th} depends upon the material type, strength, and microstructure, but for most low-strength steels it ranges from 10 to 15 $MPa \cdot m^{-1/2}$ [70–73,76,86,103,104]. An et al. [105] proved that hydrogen-accelerated crack initiation plays a more important role than fatigue crack growth with increasing hydrogen pressure. Other studies observed how the threshold value seems to be reduced by 10–25% in hydrogen environments [25,106,107]. However, open questions remain regarding the role of hydrogen in the reduction of the stress intensity threshold. In fact, spurious effects, such as the crack closure reduction related to oxide layer formation, may be more prominent than the actual effect of hydrogen [106]. Indeed, the hydrogen-induced reduction of ΔK_{th} depends on the environment, the loading parameters, and the material, making difficult its accurate prediction.

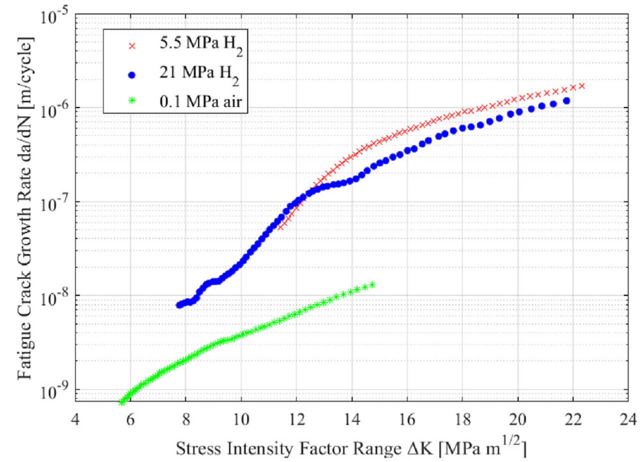

Fig. 4 – FCGR curve for an X80 steel tested in hydrogen at 5.5 and 21 MPa and in the air (adapted from Ref. [92]).

Susceptibility factors

The occurrence of environmental hydrogen embrittlement relies on the synergistic interaction of many factors. One of the most important is the type of hydrogenated environment, which comprehends pressure, temperature, hydrogen purity, form, and source. The second factor is the metal considered, from the basic crystal structure to the microstructure, heterogeneities, substructural conditions, phase stability, strength level, surface conditions, etc. The third crucial factor is the stress field, which accounts for the load type (monotonic or cyclic), the state of applied stress, and the presence of residual stress [108]. Although the effect of these factors, taken individually, has been extensively studied over the years [64,86,109], their synergistic interplay is far from being understood [58]. Fig. 5 schematically represents the interdependence of the influencing factors for the HE susceptibility of industrial equipment.

Effect of temperature

Temperature influences the hydrogen-metal interaction in many aspects, from the kinetic of surface reactions to

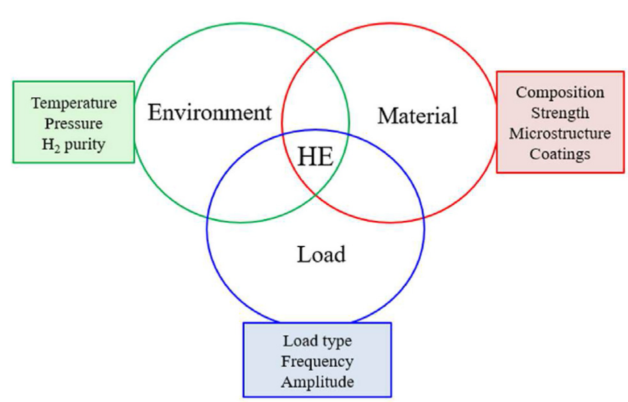

Fig. 5 – Hydrogen embrittlement susceptibility factors.

hydrogen solubility, diffusivity, and trapping. Diffusion and solubility properties are highly dependent on the material system. For instance, already at room temperature, the material diffusivity and solubility can vary up to four orders of magnitude between austenite and ferrite [110]. Temperature has strong influence on both solubility and diffusivity of iron based alloys for temperature higher than 20 °C [111]. On the other hand, when lowering the temperature, which is relevant for liquid hydrogen transport and ancillary components, such as turbo-compressors, quantum effects become relevant with respect to the material hydrogen transport properties [112].

Hence, temperature strongly influences the bulk hydrogen concentration, determining the magnitude of hydrogen-induced degradation of mechanical properties [113]. Despite this, experimental campaigns tailored to investigate the effect of temperature on HE in metals have been recently reported for high-pressure hydrogen environments [22]. Nelson and Williams [114] and Takakuwa et al. [115] tested the HEFCGR of low carbon steels (4130 and SM490B, respectively), demonstrating independently that the most severe temperature range for HE lies around room temperature, i.e., between 20 and 25 °C. On the other hand, Frandsen and Marcus [116] reported that hydrogen-induced FCGR acceleration for high-strength martensitic steels peaked at around 0 °C. This was attributable to the temperature impact on the kinetics of absorption and dissociation of molecular hydrogen. Similarly, Gangloff and Wei [117] found that the crack propagation in hydrogen was increased at −10 °C and 20 °C for 200-grade and 250-grade maraging steels, respectively. Xing et al. [118] conducted tests on X90 pipeline steel and observed that HE is maximized at temperatures around 40 °C.

San Marchi and Somerday [119] demonstrated that austenitic stainless steels, commonly used for liquid hydrogen storage, show the maximum HE susceptibility in the temperature range between −70 and −20 °C. This was motivated by the strain-induced martensite transformation (SIMT) promoted at low temperatures [28]. Yang et al. [120] observed that the resistance to HE of 304 austenitic stainless steel is reduced with decreasing temperature from 25 to −50 °C and increased again when the temperature falls below −50 °C. HE disappears at temperatures lower than −150 °C due to sluggish hydrogen diffusion. Michler and Naumann [121] proved that the temperature dependence of HE in austenitic stainless steels can be drastically reduced by increasing the Ni content above 12.5% and controlling the local metallurgy to obtain a very homogeneous microstructure. Ogata [122] tested also austenitic stainless steels and proved that HE does not manifest its effect until a certain amount of deformation, regardless of the operating temperature. Matsuoka et al. [123] observed that HEFCGR has a prominent temperature dependence at low gas pressures, while it is negligible at high pressures. Moreover, Tan et al. [124] observed that 30CrMnSi–Ni2A high-strength steel is not affected by HE at temperatures higher than 200 °C.

Overall, the effect of temperature can be explained by the hydrogen trapping model, in which the hydrogen atoms are assumed to diffuse through the metal lattice and be trapped at microstructural defects. At cryogenic temperatures, hydrogen diffuses too slowly to accumulate at trapping sites in sufficient quantities to determine severe detrimental effects on mechanical properties; on the other hand, at high temperatures, hydrogen mobility increases and atoms' de-trapping overcomes the trapping [75]. As a rule of thumb, for many metals and alloys, the HE effects tend to be more severe between −70 and 30 °C [125].

Effect of pressure

Hydrogen partial pressure is a relevant environmental parameter influencing the magnitude of HE degradation [119]. According to Sievert's law, the solubility of hydrogen in metals, intended as the total hydrogen concentration both at normal lattice and trapping sites, is proportional to the square root of its partial pressure. In other words, increasing hydrogen partial pressure will increase the hydrogen concentration in metals, which in turns eases the hydrogen-induced losses in tensile and fracture properties. By way of illustration, Fig. 6 shows the hydrogen gas pressure impact on the elongation of an X100 steel specimen.

In the case of HEFCGR, a less pronounced pressure dependence can be observed [126,127]:

$$\frac{(da/dN)_{H_2}}{(da/dN)_{air}} = 1 + N \cdot p_{H_2}^{0.36} \tag{9}$$

where N is a coefficient which depends on the material. The occupation of traps follows this dependence over a certain pressure range and shows a plateau for higher values [68,114]. This is due to the traps' saturation which occurs when the maximum amount of hydrogen has occupied all the traps that are present in the metal lattice. This saturation concentration depends on the material's microstructure, composition, and strength [128,129]. The reduction of fracture toughness of A516, API 5L Grade B, and X42 steels approaches the saturation for hydrogen pressure greater than 13.8 MPa, while the plateau is reached at 6.9 MPa for A-106 Grade B steel [86]. In general, low-strength steels have a more severe reduction in fracture toughness for increasing hydrogen pressure compared to high-strength steels [114]. The fatigue performances are also reduced for increasing hydrogen pressure, depending on the materials' microstructure and the stress intensity range [90,95,98,105,130]. At high ΔK values, the FCGR is not very sensitive to pressure variations, while at low ΔK the

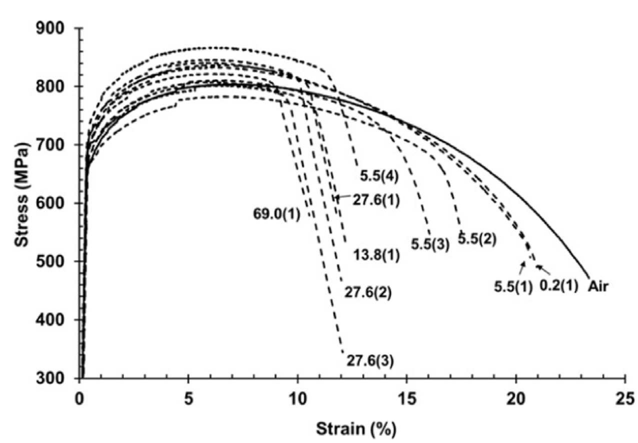

Fig. 6 – Stress-strain curves for an X100 steel tested in hydrogen at different gas pressures and in air [68].

fatigue crack growth can increase by ten folds varying the H_2 pressure from 0.02 to 100 MPa [131]. Nevertheless, the stress intensity ranges considered are often not applicable to normal operations of equipment for hydrogen handling and storage. Hence, further tests are required to confirm if these trends remain valid at lower ΔK [132–134].

Operating a component at higher hydrogen pressures increases the level of applied stress. Since hydrogen-induced degradations are triggered by the applied stress, the H_2 partial pressure has a twofold negative influence on HE susceptibility. Despite this, hydrogen is being stored and transported at increasingly high pressures to overcome the issue represented by its low volumetric energy density (3.2 times lower than that of methane [135]).

Effect of hydrogen purity

Hydrogen purity influences the hydrogen uptake into the metal. In particular, the addition of small amounts of specific gas species may reduce [86], enhance [136], or keep the HE sensitivity unchanged. Hence, gas impurities can act as inhibitors for hydrogen embrittlement by hindering the surface reactions of absorption. Oxygen is considered a promising inhibitor because it creates a passivation oxide layer which impedes hydrogen uptake [38]. Komoda et al. [40] performed fracture toughness tests on A333 Gr. 6 carbon steel in hydrogen gas with oxygen impurities, and observed how the results in hydrogen and 100 ppm oxygen were comparable with that in the air. The inhibiting effect of 10 ppm oxygen was present only at the initial stage of the crack propagation. Similarly, Kussmaul et al. [137] tested the fracture toughness of 15 MnNi 6 3 steel and obtained a complete HE inhibition with 150 ppm oxygen. Somerday et al. [138] tested the FCGR of X52 steel in hydrogen blended with oxygen impurities and observed how the results in 1000 ppm O_2 were comparable to those in the air. At lower O_2 concentrations, HE was inhibited at medium-low ΔK, while an enhancement occurred above a critical ΔK level. Cialone and Holbrook [139] tested an X42 pipeline steel in hydrogen with gaseous additives (O_2, CO, and SO_2) and obtained a nearly complete inhibition of HEFCGR [82]. Nelson et al. [131] investigated the HEFCGR of 1020 steel in different gas mixtures (hydrogen with CO_2, CH_4, and H_2O). While water reduced the fatigue crack growth, additions of carbon dioxide and methane had negligible inhibiting effects or even increased the FCGR compared to that measured in pure hydrogen. Thereafter, Bai et al. [140] observed how small additions of steam and CO_2 increased the hydrogen-induced ductility loss in a 3Cr steel. Moreover, the low HE inhibition of CH_4 was confirmed by Stayov et al. [38]. In general, both the concentration and partial pressure of gaseous impurities are considered relevant for the degree of inhibition [141]. In addition, the amount of inhibitor required to eliminate the HE effects depends on the yield strength, microstructure, chemical composition of the steel [86], and the hydrogen partial pressure [142]. Even if the addition of specific gas impurities has been proven to limit, or even eliminate, the detrimental effects of hydrogen in the short term, the benefits of inhibitors in the long term remain to be assessed [119,143]. Fig. 7 shows the ratio between the FCGR in hydrogen with additives and in pure hydrogen for a 2.25Cr–1Mo steel.

Effect of microstructure and chemical composition

The mobility of hydrogen atoms through the metal lattice is influenced by the presence of microstructural defects, dislocations, grain boundaries, non-metallic inclusions, and precipitates [122,123]. These reversible traps are considered the main responsible for HE [144–148]. Different microstructures are known to manifest dissimilar behavior in the presence of hydrogen. The martensite shows a severe hydrogen-induced degradation of mechanical properties, because of the elevated residual stress and the number of dislocations [22]. Acicular ferrite exhibits higher hydrogen diffusivity than bainite, which in turn has a higher hydrogen solubility than pearlite [149]. In general, a higher amount of cold work is associated with an increased dislocation density, implying a more pronounced reversible hydrogen trapping, and consequently a greater HE susceptibility [150].

Over the years, materials evolved in terms of microstructures and cleanliness. Hence, microstructure, composition, and mechanical properties vary between steels with the same grade that have been produced in different years and with various manufacturing techniques [22,121]. Grain refinement has also a strong influence on hydrogen embrittlement. If, on the one hand, it introduces more grain boundaries which act as barriers for hydrogen transport, on the other, it introduces more hydrogen trapping sites. Several studies demonstrated an increased HE resistance in fine-grained steels compared to coarse-grained ones. Yazdipour et al. [151] showed how hydrogen diffusion coefficients are maximized for a specific grain size, because of the two contrasting effects of grain refinement. In general, the correlation between HE susceptibility and grain size is still debated [66,69,152,153]. Grain boundary character and crystallographic texture have also a role in the material's cracking behavior [154]. High-angle grain boundaries (HAB) provide a preferential path for crack propagation compared to low-angle boundaries (LAB) and coincident lattice sites (CSL) [134,135].

Welds and heat-affected zones (HAZs) are typically the areas with the greatest defect density, thus making them prone to hydrogen-induced cracking. The presence of residual stresses, uncontrolled microstructures, weld flaws, and geometric imperfections foster crack initiation and propagation in the presence of pressurized hydrogen gas [143]. Martensite or acicular ferrite can be locally observed in the HAZs, depending on the welding procedure [155]. Many weld types with various residual stresses, microstructures, and hardness are used in industrial practice. The standard ASME B31.12 [156] indicates general acceptance criteria for welds and HAZs in hydrogen pipelines. Several contradictory results can be found in the literature regarding the HE susceptibility of welds [64]. Lower effects on fracture toughness of X70 steels have been observed in welded areas compared to the base metal [157]. This observation has been explained by the synergistic effect of microstructural features and the presence of inclusions: the ferritic and mixed bainitic-pearlitic-ferritic microstructures with elongated grains of the HAZ act as barriers to the hydrogen diffusion [158]. Lower ductility loss was also observed for X52 HAZs compared with the base metal, because of the less pronounced banded microstructure observed in the heat-affected zone [157]. Nevertheless, also

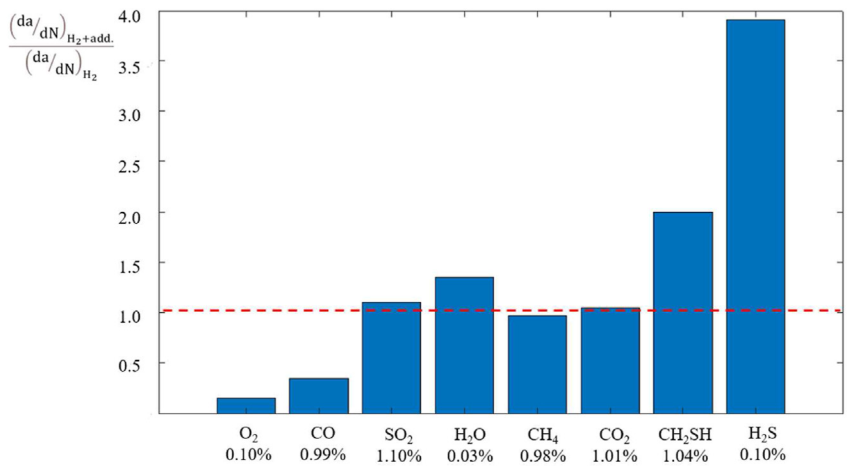

Fig. 7 – Ratio between the FCGR in hydrogen with and without gas impurities (adapted from Ref. [119]).

higher HE sensitivities were observed in HAZs for both tensile and fracture resistance properties [159]. The study of the HEFCGR gave contradictory results as well, depending on the welding process and the different microstructures present in the weld and HAZ [160,161].

The susceptibility of steels to HE depends on their chemical composition. Higher contents of carbon, manganese, chromium, molybdenum, vanadium, nickel, and copper tend to influence hardness to different magnitudes. Several correlations, known as carbon equivalent formulae, correlate the HE susceptibility of the material to its content of alloying elements. The correlation of Dearden-O'Neill is suitable to compare a large range of plain carbon and carbon-manganese ferritic steels, while other equations can be used for high-strength low-alloy steels [162]:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15} \tag{10}$$

The HE sensitivity increases for increasing values of CE. San Marchi and Somerday [119] suggested that a carbon equivalent content lower than 0.35 allows for avoiding the formation of untempered martensite during welding. In addition, the steel composition limits for hydrogen applications include sulfur and phosphorous contents lower than 0.01 and 0.015, respectively. Nevertheless, this correlation is not valid for austenitic stainless steels, as proven by Michler and Naumann [121].

Effect of strength

The relation between hydrogen embrittlement and material strength is too complex to be determined precisely. Such effect is strongly linked to the material microstructure which determines the hydrogen transport properties (i.e., diffusivity, solubility, and number of trapping sites), as well as the deformation processes and dominant degradation mechanisms. This is confirmed by the recent theory for which hydrogen-induced degradation is the results of multiple mechanisms working together [163]. The reviews from Martin et al. [51] and Djukic et al. [58] give a comprehensive summary of such phenomena and their interaction. From a more general point of view, it is commonly accepted that high-strength steels show a more pronounced HE sensitivity than low-strength ones [64,164]. This is reflected by the current acceptance criteria for steels for hydrogen piping, which specifies the maximum allowable strength [156]. The strength dependence is even more pronounced at low hydrogen pressure [114]. Three 4340 steels were tested in 0.11 MPa hydrogen gas, and the critical stress intensity factor for H_2-assisted crack extension was found to decrease four to eight times increasing the yield strength from 1145 to 1875 MPa [165]. The importance of yield strength for HE susceptibility was also confirmed for HY-80, A517 (F), and HY-130 steels [128]. Low-strength (σ_y < 700 MPa) austenitic steels are proven to manifest an elevated resistance to crack growth extension under static loads [64].

However, this strength dependence does not apply in the case of cyclic loads [25]. Clark [166] measured the HEFCGR in HY-80 (σ_y = 650 MPa) and HY-130 (σ_y = 965 MPa) specimens, and observed that the HY-80 steel had an FCGR two to 40 times higher than the HY-130, despite the lower yield strength. Tau et al. [158] demonstrated how three AISI 4130 steels with different strengths but similar microstructures had a similar fatigue performance in hydrogen gas. On the other hand, the FCGR was proven to be strength-dependent for three martensitic steels. Several studies confirmed that the HEFCGR was not strength-correlated for X42 [25], X52 [98], X70 [25], and X100 pipeline steels [132]. Other studies demonstrated that chemical composition and microstructure are the most relevant parameters affecting fatigue performance [167,168]. Hence, materials normally considered not susceptible to hydrogen embrittlement may manifest severe HEFCGR, while some high-strength steels can exhibit a comparatively low susceptibility [25,92]. The possibility to use higher strength steels for hydrogen applications is very interesting from the technical point of view since it allows to overcome unnecessarily conservative guidelines for the fitness-for-service of equipment exposed to high-pressure hydrogen gas (i.e., pipelines, cylinders, vessels, etc.) [62].

Effect of frequency and stress ratio on FCGR

Since HE is a time and stress-driven process, when focusing on FCGR performance, parameters such as frequency and stress ratio will impact its occurrence and extent. In a hydrogen environment, the FCGR is normally increased as the frequency decreases [64]. In fact, the exposure time is much higher at lower frequencies, hence more hydrogen atoms can absorb and diffuse to the crack tip within each cycle. Despite this hydrogen-enhanced FCGR at low frequencies, a limited number of test results are available for frequencies below 0.1 Hz. Holbrook et al. [126] tested the FCGR for X42 steel at 6.9 MPa and did not observe significant changes varying the frequency between 0.1 and 10 Hz. Similar results were obtained for 2.25Cr–1Mo steel tested between 0.05 and 5 Hz [169]. Nevertheless, Walter and Chandler [170] measured a fivefold increased HEFCGR for SA-105 steel, decreasing the frequency from 1 Hz to 0.001 Hz. Moreover, Matsuo et al. [171] tested tempered Cr–Mo steel in 0.7 MPa hydrogen gas gradually decreasing the frequency to 0.1 Hz. They found out that the acceleration peak was followed by a decrease in the FCGR measured in hydrogen with respect to that in the air. The ΔK at which the HEFCGR became equal to that in the air, increased for decreasing frequencies. Subsequently, Yamabe et al. [172] tested a low-carbon steel (JIS-SM490B) in hydrogen gas at 0.1–90 MPa and 0.001–10 Hz. Increasing the pressure, the acceleration peak shifted to lower frequencies. At pressures higher than 10 MPa, the FCGR gradually increased for decreasing frequency with no evidence of an acceleration peak. Slifka et al. [90] tested both modern and vintage X52 steels and two X70 steels over the pressure range 0.01–1 Hz at 5.5 MPa and 34 MPa. They observed a moderate frequency dependence at high pressure. The vintage X52 steel was less sensitive to frequency variations, while the FCGR increase at low frequency was more prominent for the modern X52 and the X70A.

Cheng and Chen [173] suggested the existence of a critical frequency below which the FCGR is not further affected by frequency variations. The critical frequency was proven to depend upon several factors, such as pressure, temperature, material strength, and microstructure [174]. Alvaro et al. [175] tested Fe–3%Si alloy and X70 steels at 0.1, 1, and 10 Hz. The experiments showed how HEFCGR was clearly frequency dependent. The da/dN curves shifted to higher stress intensity ranges with decreasing frequency. In addition, the acceleration factor of Fe–3%Si in hydrogen was up to 1000 times greater than the FCGR measured in the air. Murakami et al. [176] studied the fatigue crack growth in austenitic stainless steels and proved that, at very low frequencies, both diffusible and non-diffusible hydrogen is responsible for the HEFCGR. Matsunaga et al. [177] observed the same frequency dependence of HEFCGR also for 304 austenitic steel and ductile cast iron (DCI) both in hydrogen gas and with hydrogen-charged specimens.

In industrial practice, a sequence of load cycles with random amplitude is normally applied to the components. The stress ratio R (i.e., K_{min}/K_{max}) influences the transition between the three regimes of fatigue crack growth rate. Contradictory data exist in the literature about the effect of stress ratio on HEFCGR. Nelson [131] observed that the FCGR in 1020 steel was slightly modified varying the stress ratio from 0.15 to 0.37. Suresh and Ritchie [106] proved that an increased R tends to shift the onset of accelerated FCGR to lower ΔK. The same effect can be observed for the critical stress intensity range ΔK_{th}. The FCGR in hydrogen was approximately increased by two orders of magnitude and ΔK_{th} was decreased by 50%. On the other hand, both these values are comparable with those in the air at stress ratios higher than 0.75. San Marchi et al. [92] and Somerday et al. [138] obtained similar results for X52, X60 HIC, X70, and X80 pipeline steels.

In contrast, Cialone and Holbrook [139] tested an X42 steel in hydrogen gas and observed that the FCGR remained approximately constant up to $R = 0.4$, and increased linearly for further stress ratio increases. This effect at higher R values could be attributed to the increase in K_{max} (at constant ΔK), which approaches the fracture toughness in hydrogen gas. Similar results were also obtained for an X70 steel. Roy et al. [178] tested high-strength low-alloy steel at stress ratios ranging from 0.1 to 0.5 and observed a significant increase in FCGR for increasing R. This effect was attributed to the higher mean stress, which enhances both the hydrogen damage and the plastic damage and tends to suppress crack closure effects.

Minor cycles at high R-values followed by an underload are more representative of the normal working conditions of hydrogen storage equipment, which operates at a near-steady pressure with periodic pressure drops when it is emptied [179]. Pressurized hydrogen environments would therefore entail an FCGR acceleration due to these high R cycles. In the case of an inert environment, a peak load (overload) normally causes a reduction in fatigue crack growth rate. This trend was confirmed for a hydrogen-charged AISI 4130 steel [180]. Nevertheless, more studies are necessary to verify the effect of hydrogen on overload.

The environmental, material, and loading factors affecting the HE susceptibility of steels are summarized in Table 3, specifying the most severe conditions under which hydrogen technologies may chance to operate.

Methodologies for inspection and maintenance planning

Preventive maintenance (PM) lays down that the components are checked and serviced in a planned manner to prevent breakdowns, and maintain the physical integrity of assets [181], thus solving potential problems, and preventing unexpected system failures [182]. Ideally, a valuable PM methodology should be capable of reducing the frequency and complexity of maintenance, while ensuring maximum utilization of facilities under safe conditions [183,184]. Inspection activities are a vital part of PM strategies. It is important to clarify that the inspection itself does not reduce risk but is a fundamental activity to determine if the degradation reached a critical point or predict when a failure may occur. It allows to put plans and implement mitigation strategies before the predicted failure date [185]. It is proven that the likelihood of catastrophic accidents could be dramatically reduced by applying proper inspection activities [186,187]. The

Table 3 – Influencing factors for materials' susceptibility to HE.

Type	Factor	Greatest HE susceptibility	Notes
Environment	Hydrogen partial pressure	High hydrogen pressure	These are the normal operating conditions for equipment for hydrogen transport, handling, and storage (e.g., pipelines, vessels, and cylinders)
	Temperature	Near-room temperature for ferritic steels and lower temperature for austenitic steels	
	Hydrogen purity	High hydrogen purity	
Material	Microstructure	Untempered martensite	The material type and its manufacturing processes can be selected to minimize HE susceptibility. Equipment for hydrogen service should not present those characteristics
	Grain size	Coarse grains (debated)	
	Carbon equivalent	High carbon equivalent content	
	Strength	High strength (debated for FCGR)	
	Welds and HAZs	Without post-weld heat treatments	
Load	Frequency	Low frequency	Hydrogen storage equipment is cyclically filled and emptied with compressed hydrogen and operates with minor cycles at high R-values followed by an underload
	Stress ratio	Debated	

determination of inspection frequency has evolved over the years. The state of the art of the main inspection and maintenance strategies is provided in this section to highlight the shift from a time-based approach to a risk-based one.

Consolidated methodologies

Time-based maintenance (TBM) is a traditional maintenance strategy in which maintenance activities are carried out with predetermined schedules [182], and mainly at regular time intervals [188,189]. This model assumes that the possibility of failure depends entirely on the age of the component. The failure trends show how a component experiences decreasing failure rates in the first period of its life cycle, followed by a roughly constant failure rate during the normal operating life. Then, at the end of the component's life cycle, the failure rate tends to increase again [190]. This implies that two pieces of equipment of the same type and age have the same failure rate, regardless of the events that have occurred during their service life [191]. The TBM starts by gathering failure time data for each component. Then, the dataset is analyzed through statistical models (e.g., the Weibull distribution [192]) to estimate the failure trend of the specific component. The decision-making process is the third step, which is composed of an operational cost assessment, aimed at calculating both the failure cost and the preventive maintenance cost, and an equipment mechanism assessment, aimed at classifying the component as repairable or non-repairable. Finally, the appropriate policy can be selected and implemented [190]. Fig. 8 shows a block diagram with the four main steps of the time-based inspection approach.

The TBM methodology is a relatively straightforward procedure, but in real practice, it presents several significant drawbacks. Firstly, the collection of failure time data is a challenging and time-consuming task. In addition, several studies indicate that the share of age-related equipment failures accounts only for 15–20% of the total, while the rest is caused by random events happening during the service life of the assets [191]. Another drawback of the TBM strategy is that all operating conditions are assumed to remain constant, which is rarely correct in practice [193]. All these limitations resulted in the progressive adoption of different methodologies based on equipment operating conditions and associated material degradations.

It is proven that 99% of all machine breakdowns are preceded by premonitory signs that allow to forecast the failure occurrence [194]. In this light, condition-based maintenance (CBM) planning is based on a combination of data-driven reliability models and sensor data [195]. The CBM strategy aims at performing a real-time assessment of equipment conditions in order to plan inspections and reduce the cost of unnecessary maintenance activities. The condition monitoring process is capable of collecting data from the plants' items (online or offline) to understand their deterioration patterns [190]. It can be performed continuously, periodically, or non-periodically [195]. While continuous monitoring allows to know in real-time the equipment conditions, it is associated with high costs and potentially inaccurate information [196]. The main drawback of periodic and non-periodic monitoring is the risk of losing relevant information

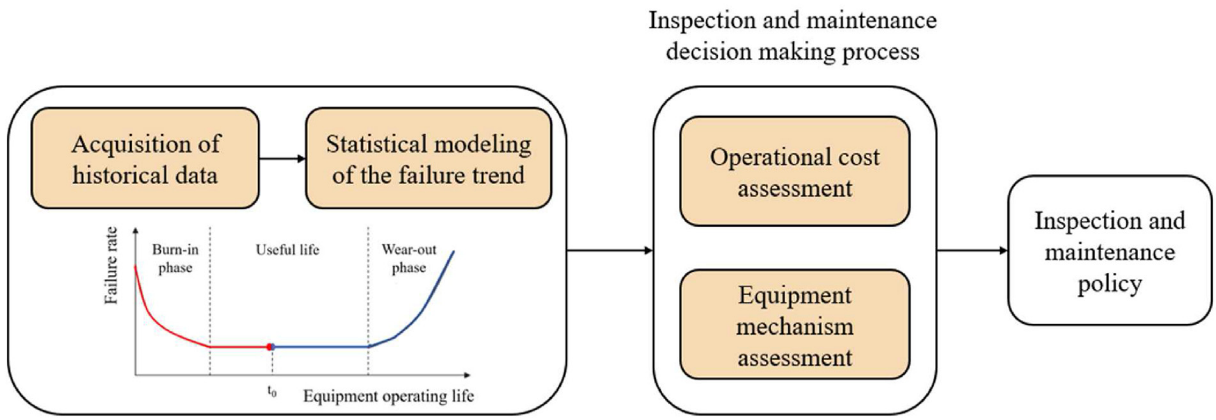

Fig. 8 – Block diagram of the TBM methodology.

between two inspection intervals [190]. Various techniques are commonly used to control equipment conditions (e.g., vibration and sound monitoring, oil and wear particle analysis, temperature, electrical, and physical condition monitoring) [190,193]. There are several standards for monitoring the conditions of industrial equipment. For instance, API 653 [197], API 510 [198], and API 570 [199] provide minimum requirements for maintaining the integrity of storage tanks, pressure vessels, and piping systems, respectively.

After the condition monitoring process, the fault diagnosis and prognosis are normally carried out. While the former lies in providing early warning signs that a certain component is operating under deteriorated conditions, the latter consists in predicting when the failure might occur [190]. Recent systems have relied on artificial intelligence techniques, such as expert systems, neural networks, fuzzy logic, and model-based systems, to strengthen the robustness of the diagnostic systems [193]. Then, the maintenance decision is taken through two approaches: the current condition evaluation-based (CCEB), which estimates the equipment condition at present, and the future condition prediction-based (FCPB), which predicts the conditions under which the equipment will be in the future [190]. Fig. 9 shows the block diagram of the condition-based approach for maintenance planning.

On many occasions, the CBM policy has been compared with traditional time-based approaches, proving that it is preferable to TBM when the inspection cost is minor, and the repair cost is higher [182], and when the inspections are scheduled during the component's useful life or later [201]. Kang et al. [202] adopted the CBM methodology for offshore wind turbines and proved that it is capable to lower the costs by 32.5% compared with traditional periodic maintenance. Ganesh et al. [203] discussed a systems architecture for the CBM data flow, implemented it in the continuous manufacture of oral solid drug products, and proved its superiority over the traditional TBM in proactively monitoring and managing future system failures. Liang et al. [204] applied a CBM model based on a continuous-time semi-Markov chain (CTSMC) to concrete bridges, showing its potential to lower overall maintenance costs. In addition, Zeng and Zio [205] combined statistical and condition-monitoring data, proving an increased effectiveness thanks to additional information on system-specific characteristics.

Risk-based inspection methodology

Nearly all major industrial accidents resulted from a failure in understanding or managing risk. Hence, the risk-based

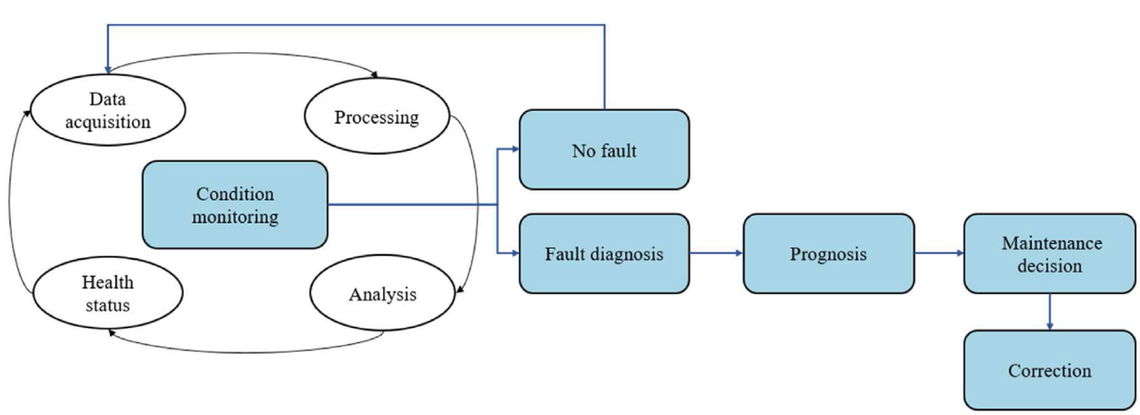

Fig. 9 – Block diagram of the CBI methodology (adapted from Ref. [200]).

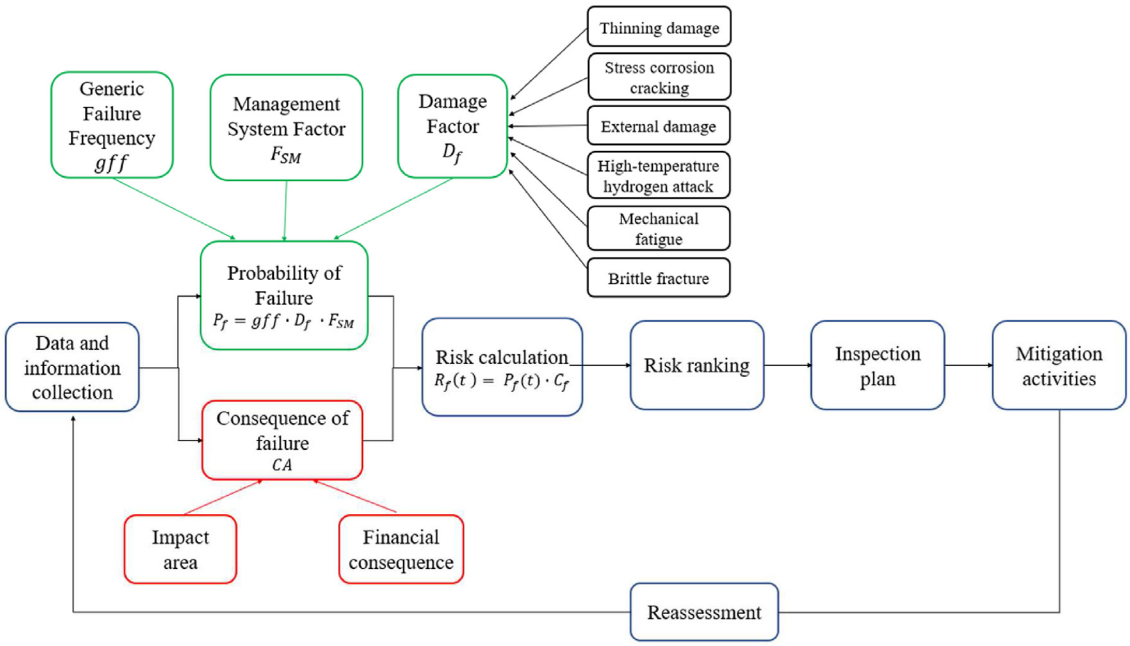

Fig. 10 – Flow diagram of the RBI methodology.

inspection (RBI) methodology, developed by the American Petroleum Institute, is focused on minimizing the risk of loss of containment and providing mitigation measures to avoid major consequences in the case of hazardous releases [206]. It assumes that, in most plants, a significant percentage of the total risk is associated with a relatively small number of equipment items. Then, the risk management efforts are focused on these high-risk components, prioritizing their inspection and maintenance to guarantee the greatest benefit in reducing the total risk [164]. The calculation of the risk is determined by combining the probability of failure $P_f(t)$ with its consequences C_f:

$$R_f(t, I_E) = P_f(t, I_E) \cdot C_f \tag{11}$$

where t represents the time and I_E is the inspection effectiveness.

The RBI procedure can be qualitative, quantitative, or semi-quantitative. Several software tools can help the analyst in managing the amount of information required for performing a quantitative RBI. For instance, DNVGL developed the commercial software *Synergi Plant – RBI* for optimizing a risk-based inspection strategy [207], while Antea Group created the integrated management system *Inspection Manager* to catalogue the items starting from the P&ID [208,209]. The RBI procedure starts with the step of data collection and validation. Secondly, the risk analyst must identify the damage mechanisms likely to occur for each piece of equipment and calculate the probability of failure for each damage. Then, the analyst must determine the risk for each component. All the equipment items should be ranked according to their risk level to develop the inspection plan, and eventually, to implement mitigation activities (e.g., maintenance or replacement of damaged components) [210]. A simplified flow diagram of the RBI methodology, as described in API 580 [185], is illustrated in Fig. 10.

Several standards and recommended practices provide guidelines for the implementation of the RBI methodology. The recommended practice API 581 [211] provides tables, algorithms, equations, and models to carry out quantitative RBI planning. API 580 and ASME PCC-3 document the essential elements of a qualitative RBI for the chemical and petrochemical industries [185,212], while EN 16991 is also applicable to other industrial sectors [213]. In addition, DNVGL-RP-G101 describes a specific RBI methodology for the upstream offshore topside equipment [214].

To sum up, the main advantages and disadvantages of time-based, condition-based, and risk-based approaches for inspection and maintenance planning are summarized in Table 4.

Probability of failure

The probability of failure of a component is calculated through the product of the Generic Failure Frequency, gff, the Damage Factor, D_f, and a Management System Factor, F_{SM}:

$$P_f(t, I_E) = gff_{total} \cdot D_f(t, I_E) \cdot F_{SM} \tag{12}$$

The gff represents the failure frequency of a certain type of equipment item operating in a relatively benign service. API 581 provides the release frequencies for several pieces of equipment and four breakage sizes, from small leaks to ruptures. The gff_{total} for the component is the sum of the gff calculated for each hole size [211]. These data have been mostly obtained from the chemical and petrochemical industries. The vast operational experience with pipes and pipelines, valves, tanks, vessels, heat exchangers, compressors, and safety equipment allowed the accurate calculation

Table 4 – Advantages and disadvantages of TBI, CBI, and RBI.

	Time-based
Advantages	• Requires minimal training for technicians • Easy to implement • Predictable schedule • Effective for continuously running assets
Disadvantages	• Ignores the real operating conditions of the equipment • Too frequent maintenance introduces risk • Ineffective for assets running occasionally • Increases costs from excessive maintenance
	Condition-based
Advantages	• Increases the asset availability • Effective for both continuously and occasionally running assets • Lower possibility of asset failure • Lower direct inspection and maintenance cost
Disadvantages	• Unpredictable maintenance indicators • Requires sensors and monitoring equipment • Requires high training for technicians
	Risk-based
Advantages	• Increases the asset availability • Effective for both continuously and occasionally running assets • Minimal possibility of asset failure • Minimal direct inspection and maintenance cost • Enables risk-informed decisions • Enhances efficiency in maintenance management • Reduces the risk
Disadvantages	• Time-consuming when implemented for the first time • Requires historical data from the plant or similar facilities • Lacks objective criteria to assess the risk and is based on experts' judgements

of the failure frequency of these components. Even if these equipment items are used in the hydrogen industry, their gff can be easily determined. This is not the case with other H_2-specific components, such as fuel cells and electrolyzers. Their limited market penetration results in a dearth of equipment reliability data, thus making the determination of their gff inherently challenging. The damage factor adjusts the gff considering the real operating conditions of the component, its susceptibility to a damage mechanism, and the escalation rate of the damage. The D_f depends on the service time and inspection effectiveness and accounts for historical inspection data together with future scheduled inspections. Damage factors are provided for the following categories of damage mechanisms [215]:

- Thinning damage;
- Stress corrosion cracking;
- External damage;
- High-temperature hydrogen attack;
- Mechanical fatigue;
- Brittle fracture.

Among the brittle fractures, HE is not even mentioned and the factors determining the material's susceptibility are not accounted for. In addition, the pressure fluctuations in pipeline systems or the filling-emptying cycles in pressurized tanks can result in mechanical fatigue, which is highly enhanced in hydrogenated environments. The hydrogen effect on FCGR and crack initiation is not considered in the existing RBI codes and guidelines. Finally, the Management System Factor is based on the evaluation of a facility management system that affects the plant's risk. This factor is applied equally to all the components of a unit, and consequently, it does not modify the order of the equipment items ranked on a risk basis [185]. Fig. 11 shows the effect of inspection and maintenance activities in terms of reduced probability of failure and consequent risk mitigation.

Consequence of failure

The consequences of an undesired release are determined using well-established consequence analysis techniques, and they are expressed in financial terms or as an affected area. The impact area derives from the calculation of the thermal radiation and overpressure [216–219]. On the other hand, the effects of toxic releases are quantified as the overexposure of personnel to hazardous substances. Cloud dispersion simulations are used to calculate the amount of flammable substances released and the extent and duration of personnel exposure to toxic releases. Financial consequences include losses due to business interruption and costs associated with environmental harm.

API 581 provides methodologies for two levels of consequence analysis. The Level 1 assessment is a simplified method for the estimation of the impact areas. It only requires basic fluid properties, operating conditions, and release rates as input data. The Level 1 assessment should be considered as a preliminary analysis, but its results are not reliable as an estimation of the actual consequences of hazardous releases. Level 2 analysis is more rigorous, since it provides fluid physical properties, performs flash calculations to determine the release phase, accounts for two-phase releases, and assesses the quantity of flammable material released or the

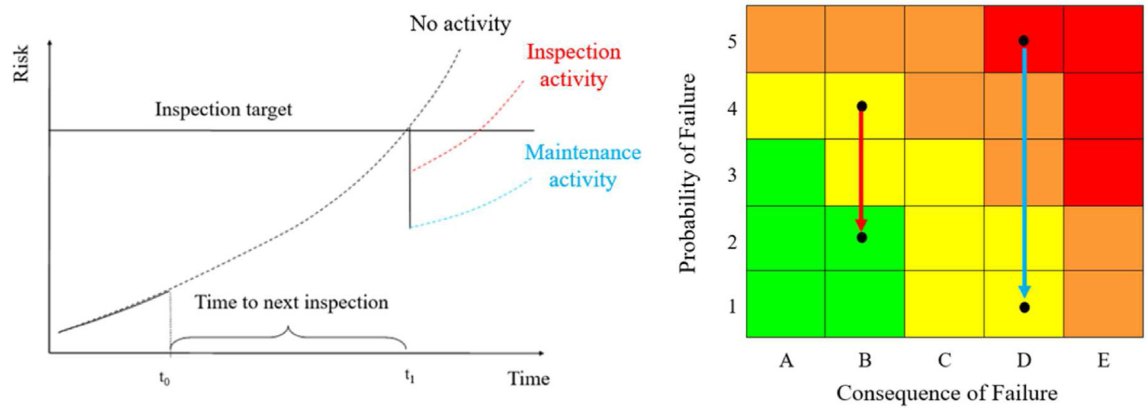

Fig. 11 – Effect of inspection and maintenance activities on the risk level.

toxic concentration. Nevertheless, this analysis is much more complex and requires a vast amount of input data [211].

Examples of application of RBI

Examples of the conventional fields of application of the RBI methodology are provided in this subsection. The American Petroleum Institute developed the RBI methodology for the chemical and petrochemical industries. Hence, this approach has been applied in the oil and gas sector from the upstream (for separator vessels [187] and offshore platforms [220]) to the downstream (for desulphurization reactors [208], sour water stripper units [209], sour crude-oil processing plants [221], crude-oil desalters [222], petrochemical reforming reaction systems [223], and refineries in general [224]). In addition, several examples related to the transportation of hydrocarbons [181] and the distribution to the end-users [186,225] are available in the literature. Various works compared the traditional inspection and maintenance policies with the RBI for single pieces of equipment [226,227] or for entire processing plants [228]. They all proved the benefits of RBI in terms of both cost and risk reduction, still respecting the availability requirements. This approach was applied to plan the inspections of a direct coal liquefaction facility [229] and to manage the shutdowns of an LNG production plant [230], where a variety of damage mechanisms are likely to occur.

RBI can be adopted for offshore static equipment according to the recommended practice DNVGL-RP-G101 [214]. Arzaghi et al. [231] applied a dynamic RBI methodology to subsea pipelines subjected to mechanical fatigue; Davatgar et al. [232] planned the inspections of the FPSO platform Goliat, while Yeter et al. [233] used the RBI methodology for offshore wind turbine farms. This scheduling framework was also used in the naval sector to reduce maintenance costs and increase the availability of a large-scale ship [234]. In the energy sector, the RBI methodology was successfully applied to entire power generation plants [235,236], as well as to single components (e.g., steam turbines) [235]. Moreover, in 2000, the European Commission produced a report to develop a methodology to identify safety-significant categories for nuclear plants and to optimize the targeting of inspections [237]. Nilsson [238] thereafter developed a quantitative RBI for a nuclear power plant in Oskarshamn (Sweden).

In the manufacturing industry, Stefana et al. [239] applied a risk-based framework capable of integrating occupational safety and health (OHS) and process safety, using as a case study three real events that occurred in the steel industry. Moreover, Marmo et al. [240] used recursive operability analysis (ROA) and fault tree analysis (FTA) to support RBM policies in an ultra-pure silicon wafers production plant. The RBI approach was also adopted to optimize inspection and maintenance activities in the water distribution system, often in combination with other techniques, such as analytic hierarchy process (AHP) [241], fuzzy inference system (FIS) [242], and multi-attribute value theory (MAVT) together with portfolio decision analysis (PDA) [243].

The main fields of application of the RBI policy, the case studies, and the techniques adopted in combination with RBI are summarized in Table 5.

Systematic review

The results of the systematic review regarding the applications of the RBI methodology to hydrogen technologies are presented in this section. A quantitative analysis of the state of the art is provided through co-authorship patterns, collaboration network maps between different countries and research groups, citation networks, and recurring keywords. After the selection of the queries and the application of the filters (reported in Table 1), a total of 106 papers were found. All these records were preliminarily screened by title, keywords, and abstract. After the screening procedure, 70 papers were included and assessed for eligibility through full-text reading. A total of 47 articles were selected as eligible for the systematic review, and other 19 relevant papers were identified through forward-backward searches. The systematic review process is summarized in Table 6, specifying the number of records excluded and the reason for exclusion.

As mentioned in the Methodology section, no limitations on the publication year were introduced. Fig. 12 shows the

Table 5 – Relevant examples of application of the RBI methodology.

Field of application	Case study	Authors	Year	Type of analysis	Techniques	Reference
Onshore chemical and petrochemical industries	Refinery	Bertolini et al.	2009	Semi-quantitative	RBI	[224]
	Petrochemical reforming reaction system	Hu et al.	2009	Semi-quantitative	RBI + PAR[a]	[223]
	Propane pre-cooled mixed refrigerant plant for LNG production	Keshavarz et al.	2012	Quantitative	RBI	[230]
	Large-scale crude oil tanks	Shuai et al.	2012	Quantitative	RBI	[226]
	Vessel in a crude oil distillation unit	Shishesaz et al.	2013	Qualitative	RBI	[227]
	Liquefaction unit in an LNG processing plant	Hameed and Khan	2014	Quantitative	RBI	[228]
	Oil and gas separator vessel	das Chagas Moura et al.	2015	Quantitative	RBI + MOGA[b]	[187]
	Crude oil desalter and atmospheric tower	Lagad et al.	2015	Qualitative	RBI + IOW[c]	[222]
	Sour water stripper unit in a refinery	Vianello et al.	2016	Quantitative	RBI	[209]
	Coal-to-liquid manufacturing	Dou et al.	2017	Qualitative	RBI	[229]
	Malaysian petrochemical and chemical industries	Mohamed et al.	2017	Qualitative	RBI	[244]
	Pipeline carrying mixture containing sulfuric acid	Bhatia et al.	2019	Quantitative	DRBI[d]	[181]
	Desulphurization reactor of an isomerization plant	Vianello et al.	2019	Quantitative	RBI	[208]
	Sour crude oil processing plant	Marhavilas et al.	2019	Qualitative	e-HAZOP (HAZOP[e] + DMRA[f] + AHP[g])	[221]
	Oil and gas production and processing unit	Rachman and Ratnayake	2019	Quantitative	RBI + ML[h]	[183]
	Natural gas regulating and metering station	Leoni et al.	2019	Quantitative	RBI + BN[i]	[225]
	Natural gas regulating and measuring station	Leoni et al.	2021	Quantitative and semi-quantitative	RBI + HBN[j] + FMECA[k]	[186]
Offshore	Subsea pipelines	Arzaghi et al.	2017	Semi-quantitative	DRBI + BN	[231]
	Offshore facility platform	Yazdi et al.	2019	Semi-quantitative	DRBI + IFAHP[l]	[220]
	Offshore wind turbine farm	Yeter et al.	2020	Semi-quantitative	RBI	[233]
	FPSO platform Goliat	Davatgar et al.	2021	Semi-quantitative	RBI + BTA[m] + TEC2O[n] + REWI[o]	[232]
Maritime	Naval vessels and ships	Cullum et al.	2018	Quantitative	RBI + ML + DT[p]	[234]
Energy industry	BWR nuclear power plant in Oskarshamn	Nilsson	2003	Quantitative	RBI	[238]
	Steam turbine plant	Fujiyama et al.	2004	Quantitative	RBI + RA[q]	[245]
	Thermal power generation plant	Krishnasamy et al.	2005	Quantitative	RBI	[235]
	Piping system of a 1000 MW ultra-supercritical power plant	Song et al.	2021	Quantitative	RBI	[236]
Manufacturing	Production plant of ultra-pure silicon wafers	Marmo et al.	2009	Quantitative	RBI + ROA[r] + FTA[s]	[240]
	Steel and iron industries	Stefana et al.	2022	Quantitative	IMPROSafety[t]	[239]
Water pipelines	Isolation valves in the water supply network	Marlow et al.	2012	Semi-quantitative	RBI + AHP	[241]
	Underground sewerage network	Mancuso et al.	2016	Semi-quantitative	RBI + MAVT[u] + PDA[v]	[243]
	Water distribution network	Phan et al.	2019	Semi-quantitative	RBI + FIS[w]	[242]

[a] PAR: Proportional Age Reduction model.
[b] MOGA: Multi-Objective Genetic Algorithm.
[c] IOW: Integrity Operating Windows methodology.
[d] DRBI: Dynamic Risk-Based Inspection.
[e] HAZOP: Hazard and Operability Analysis.
[f] DMRA: Decision-Matrix Risk Assessment.
[g] AHP: Analytical Hierarchy Process.
[h] ML: Machine Learning.
[i] BN: Bayesian Network.
[j] HBN: Hierarchical Bayesian Network.
[k] FMECA: Failure Modes, Effects and Criticality Analysis.
[l] IFAHP: Intuitionistic Fuzzy Analytic Hierarchy Process.
[m] BTA: Bow-Tie Analysis.
[n] TEC2O: Technical, Operational and Organizational Factors.
[o] REWI: Resilience-based Early Warning Indicators.
[p] DT: Decision Theory.
[q] RA: Reliability Analysis.
[r] ROA: Recursive Operability Analysis.
[s] FTA: Fault Tree Analysis.
[t] IMPROSafety: Integrated risk Management for Process and Occupational Safety.
[u] MAVT: Multi Attribute Value Theory.
[v] PDA: Portfolio Decision Analysis.
[w] FIS: Fuzzy Inference System.

Table 6 – Studies included in the systematic review.

Phase	Description	Records included	Records excluded	Reasons for inclusion or exclusion
Identification	Records for WoS CC database search	107		
	Records after filters applied	106	1	Language other than English
Screening	Records screened by title, keywords, and abstract	70	36	Unrelated to hydrogen Unrelated to inspection and maintenance
Eligibility	Full-text articles assessed for eligibility	47	23	Unrelated to hydrogen embrittlement Present post-mortem analysis only
Inclusion	Additional records identified	19		Related to NDT to detect HE Related to RBI for hydrogen technologies
	Total number of studies included	66		

time distribution of publications related to this research topic. The plotted trend fairly reflects how much attention this scientific field is receiving [246]. The time distribution shows how the research interest in this topic has globally been increasing over the last 12 years, even with some fluctuations.

Fig. 13 summarizes the main journals and conference proceedings where these records have been published. As shown, most of the top-ranked journals, i.e., *Engineering Failure Analysis*, *Corrosion*, and *Material Performance*, cover the material science domain, while some others (e.g., *Journal of Ship Production and Design* and *Journal of Pressure Vessel Technology*) are related to engineering design of mechanical components. In addition, the *Journal of Loss Prevention in the Process Industries* is related to risk assessment and safety.

The journals' ranking in Fig. 13 is reflected by the distribution of the records by topical area, which shows how most of the papers are related to material science and metallurgy, while only a few records address the topic of safety, maintenance, and risk assessment. The distribution by topical area is shown in Fig. 14 and includes only the categories defined by WoS CC.

Table 7 shows the first ten authors with the highest number of publications in the field, specifying their number of publications and citations, as well as their country and institution. Raouf Ibrahim, from the Wayne State University (USA), is the author with the highest number of publications (i.e., six papers), followed by the other nine authors with two papers each.

Even if Raouf Ibrahim has a relatively high number of papers, he has a comparatively small number of citations, thus proving the lack of connections with other researchers in the same scientific field. This observation is confirmed by the co-authorship and co-citations network maps, in Figs. 15 and 16, respectively. The co-authorship network map provides information about the various research groups and their connections and it can be useful for new researchers as long as

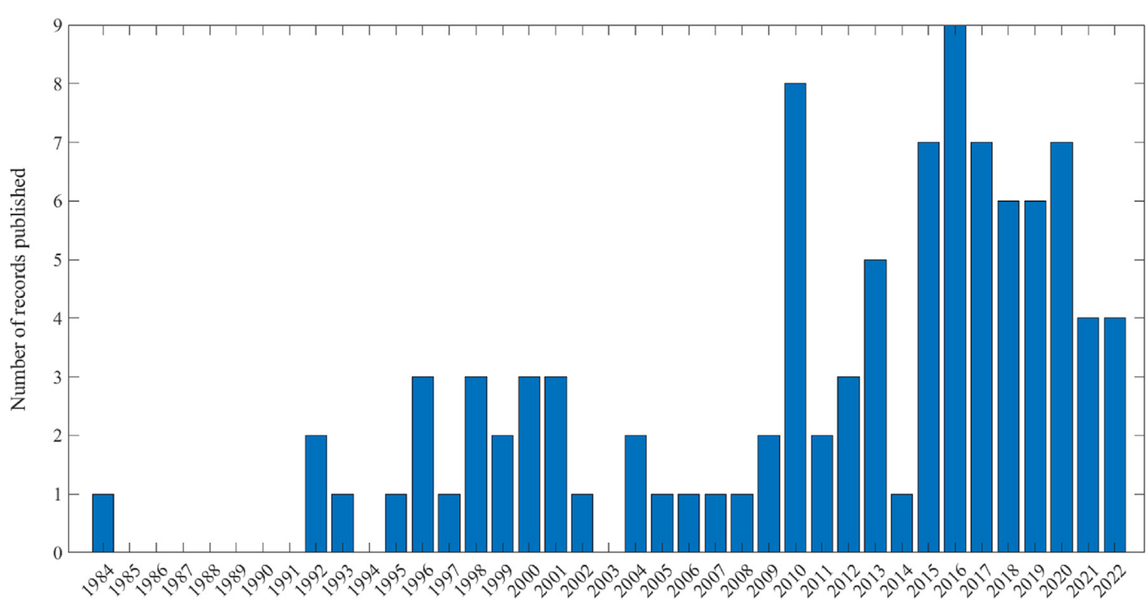

Fig. 12 – Publication year of the papers selected from the database WoS CC.

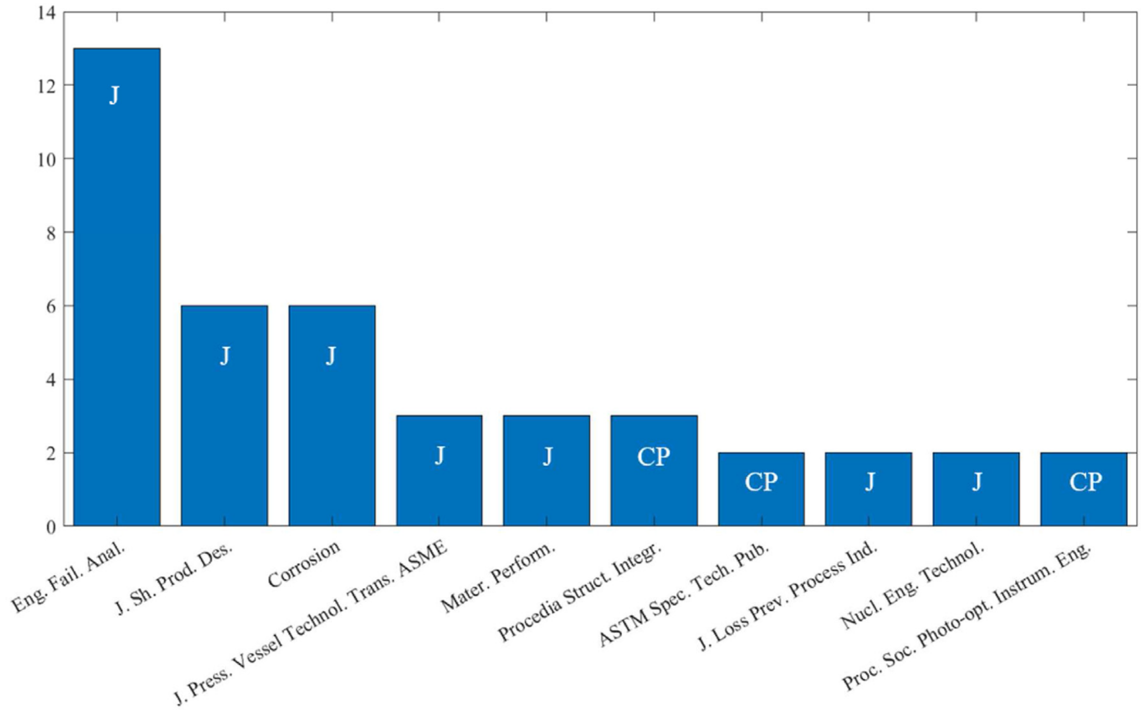

Fig. 13 – Source journals (J) and conference proceedings (CP) of the records from WoS CC.

external stakeholders [247]. Different clusters are marked with different colors, while the node size represents the number of publications per author. The large number of autonomous clusters makes it immediately clear the lack of connections between different research groups.

This poor co-authorship network is reflected by the connections per institution in Fig. 17. The University of Belgrade and the University of Defence turn out to be the best-connected institutions, thanks to the number of active researchers in the field.

Finally, a co-occurrence network map was created for the keywords with a minimum of 10 occurrences in the selected papers. The map is depicted in Fig. 18 and shows that the most co-occurrent keywords present in the records gathered from WoS CC are related to material damages: “hydrogen embrittlement”, “embrittlement”, “failure”, “cracking”, “fracture”, and “corrosion”. In addition, several keywords, such as “resistance”, “fracture toughness”, “mechanical properties”, “strain rate”, and “elastic-plastic fracture mechanics”, are related to the materials’ properties which are eventually

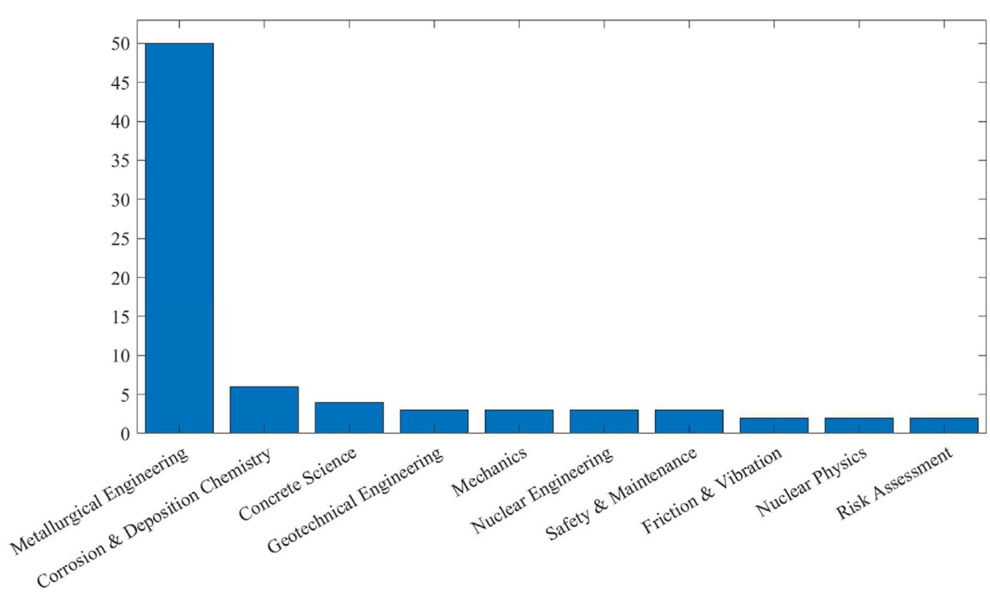

Fig. 14 – Records from WoS CC sorted by topical area.

Table 7 – Top ten authors by number of published papers and number of citations.

Author	Country	Institution	No. Of documents	No. Of citations
Ibrahim R. A.	USA	Wayne State University	6	13
Djukic M. B.	Serbia	University of Belgrade	2	104
Pluvinage G.	France	FM.C	2	22
Dodic M.	Serbia	University of Defence	2	21
Krstic B.	Serbia	University of Defence	2	21
Rebhi L.	Serbia	University of Defence	2	21
Trifkovic D.	Serbia	University of Defence	2	21
Matsunaga H.	Japan	Kyushu University	2	19
Gibbons M. R.	USA	Lawrence Livermore National Laboratories	2	12
Richards W. J.	USA	McClellan Nuclear Radiation Center	2	12

decreased by HE. Moreover, some other keywords are associated with reliability and risk-based inspection: “reliability index”, “probability of failure”, “life prediction”, and “inspection”.

Discussion

The RBI methodology directly correlates the type of material degradation that leads to equipment failure to the inspection that can potentially reduce the associated risk. Wang et al. [248] used the RBI methodology and a semi-quantitative failure modes and effects analysis (FMEA) to plan the inspection of a continuous catalytic methane reforming plant. This approach allowed for determining a risk-informed maintenance strategy. Nevertheless, no details regarding the damage mechanisms affecting each component (e.g., hydrogen compressors) are provided. Recently, Defteraios et al. [249] adopted a risk-based approach to planning the inspections of a methane steam reforming plant for hydrogen production. Considering the operating conditions, the metallurgy and other variables, equipment exposed to hydrogen was classified as susceptible to hydrogen embrittlement and high-temperature hydrogen attack. The determination of the

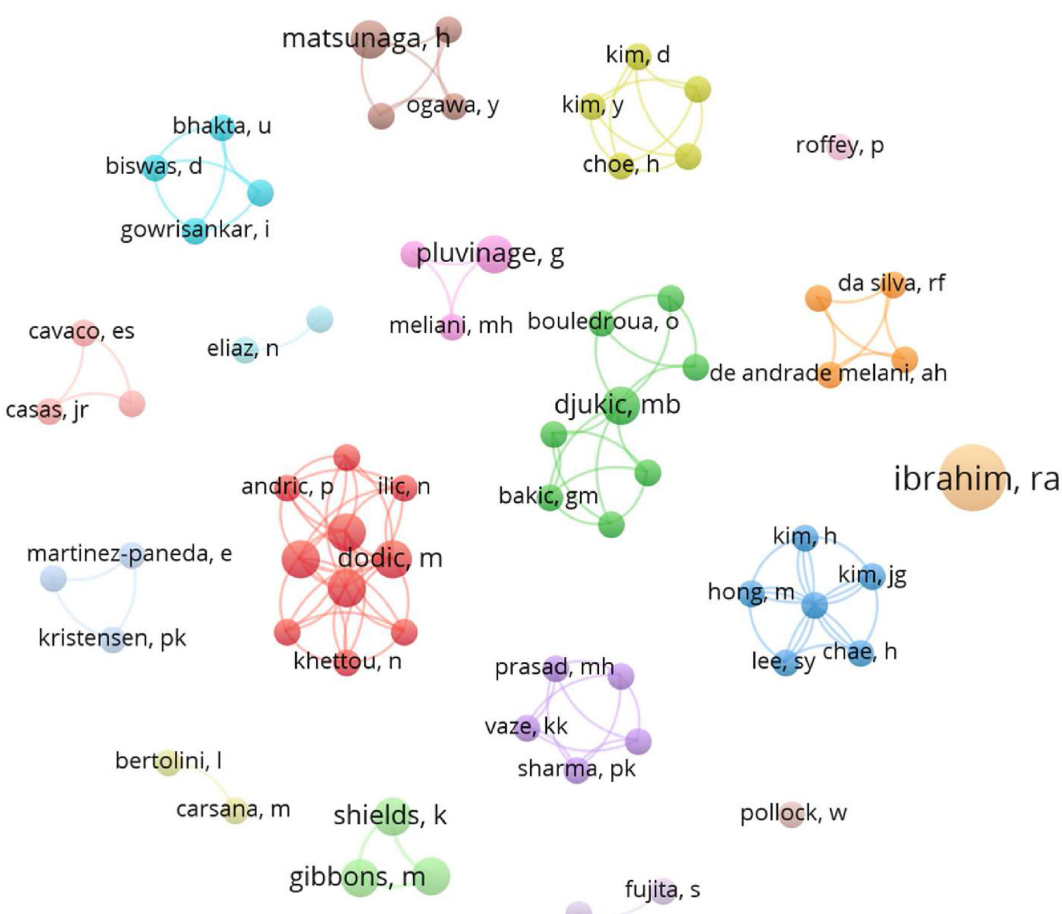

Fig. 15 – Co-authorship network map weighted on the number of publications.

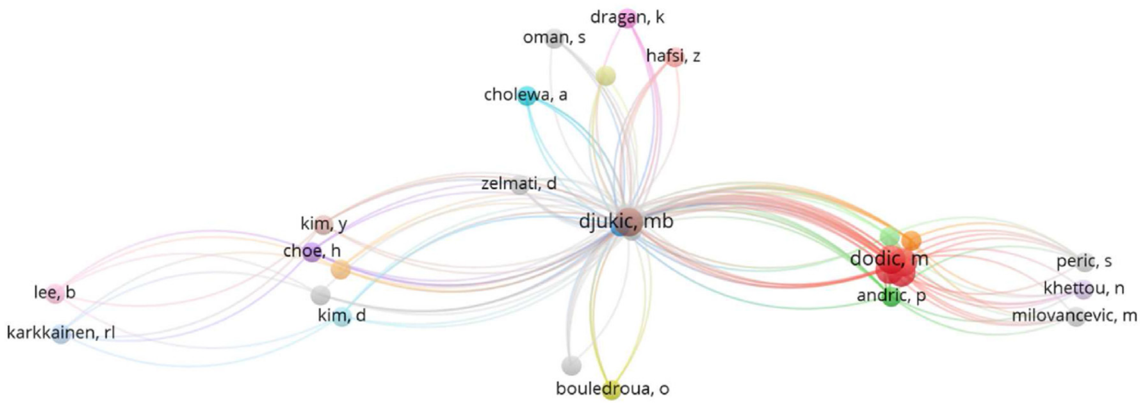

Fig. 16 – Largest set of co-citations weighted on the number of publications.

Fig. 17 – Largest set of co-authorship connections (per institution) weighted on the number of publications.

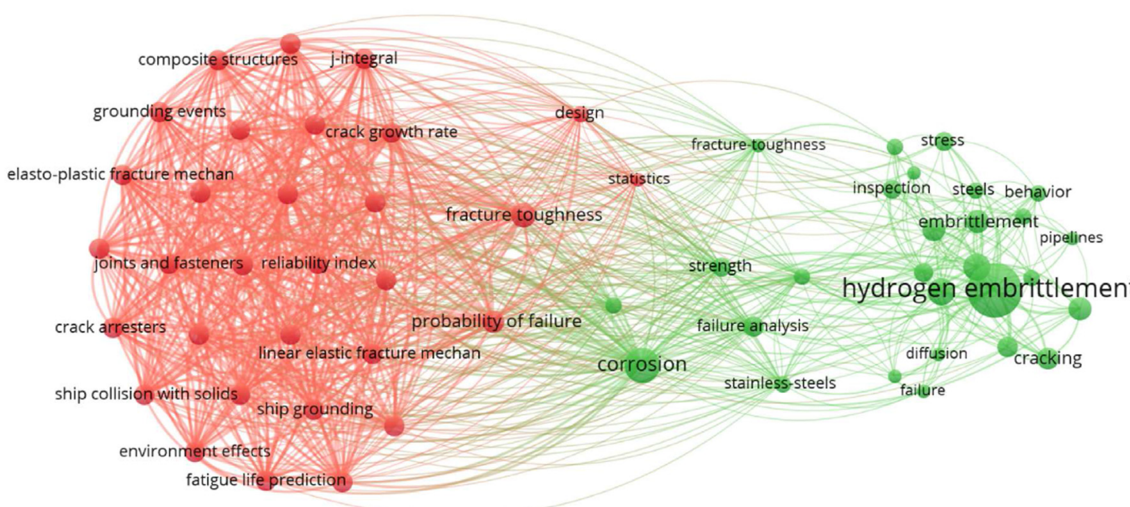

Fig. 18 – Co-occurrence map for the keywords.

probability of failure was based on condition monitoring performed through non-destructive techniques (NDT).

A limited number of hydrogen damages are considered in the current version of the RBI standards and recommended practices. Moreover, a procedure to calculate the damage factor for HE is missing, and other damage mechanisms, although they require the presence of hydrogen as a by-product of acidic substances, do not apply to H_2 environments [250]. On the one hand, the inaccurate evaluation of the probability of failure increases the uncertainty, thus overestimating the risk associated with equipment for hydrogen handling and storage. On the other hand, if the damaging effects of HE are neglected or improperly associated with other degradation modes, the resulting risk might be underestimated. Ustolin et al. [251] recently reviewed the standard EN 16991 and suggested several modifications for the future application of the RBI methodology to technologies exposed to pure compressed gaseous hydrogen. In addition, Campari et al. [250] proposed a review of the existing RBI standards and highlighted how the RBI approach can be adopted to optimize the inspection planning of hydrogen technologies only with an additional level of uncertainty.

Non-destructive tests can be used to evaluate the material integrity and the presence of internal defects or surface cracks without changing the original characteristics of the component. NDT is the most used method for inspecting a component for hydrogen service without damaging the material or jeopardizing its fitness-for-service [252]. Given its complexity, the detection of hydrogen embrittlement often requires using a variety of non-destructive tests. Visual inspections (VI) and remote visual inspections (RVI) allow the detection of macroscopic surface flaws only; hence, they are not reliable in identifying hydrogen-induced cracks [253]. Ultrasonic testing (UT) is based on the transmission of high-frequency sound waves through the material to detect any internal modification. Radiographic tests (RT) use X or gamma radiation to detect internal defects and fractures, but they are often not sufficiently sensitive to detect HE microcracks [215]. Magnetic particle testing (MT) or wet fluorescent magnetic particle testing (WFMT) can detect surface or sub-surface defects in ferromagnetic materials by looking for perturbations of magnetic fields within it [252]. Phased array ultrasonic testing (PAUT) and short wave ultrasonic testing (SWUT) allow the finding and sizing of hydrogen-induced cracks with very good precision [215]. Acoustic emissions (AE) can detect any change in the component's mechanical behavior when exposed to hydrogen, but the results are often difficult to interpret [254] and they require expensive equipment [253].

The systematic review resulted in a limited batch of papers, considering the specificity of the topic. The records gathered from the Web of Science database belong to different research fields mostly related to materials science and metallurgy. Only a few papers have a clear and explicit connection with safety, inspection and maintenance, or risk assessment. Another interesting trend resulting from the SR is the number of publications over the years. From the analysis, it turns out that the scientific activity on this topic increased over the last 12 years. Nevertheless, this generally rising trend presents some fluctuations and is less pronounced than might be expected, given the growing interest of both governments and private stakeholders in hydrogen technologies and particularly in hydrogen safety. The ranking of authors by number of publications and number of citations shows how the USA, Serbia, France, and Japan have the most active research groups. Raouf Ibrahim from Wayne State University is the author with the most publications in the field, while Milos Djukic from the University of Belgrade is the most cited author. In addition, the co-authorship and co-citations network maps show a significant number of independent and unconnected clusters. This fact might be because material science and safety have been mostly considered two well-distinguished research fields. The scientific community working on hydrogen embrittlement is relatively small but well-connected. On the other hand, the researchers addressing the topic of H_2 safety mainly concentrated on modeling and simulating undesired hydrogen releases in the environment. The connection of hydrogen-induced material degradations and their impact on predictive maintenance, inspection planning, and estimation of the remaining useful life of hydrogen technologies is a virtually unexplored research field. In such a context, the studies on this topic are mostly conducted by groups that are actively investigating HE or hydrogen safety, but rarely both topics. This is proven by the a lack of collaboration, not only between researchers from different countries but also between different institutions within the same country.

Conclusion

In this study, an overview of hydrogen embrittlement, its effect on material properties, and the factors determining the materials' susceptibility is provided. Moreover, the most effective inspection and maintenance planning approaches are explained, focusing on the RBI methodology. A systematic review regarding the adoption of this approach for inspecting and maintaining industrial equipment exposed to the degrading effect of HE is presented, highlighting a dearth of studies on this topic. This field is inherently multidisciplinary since it represents the link between materials science and RAMS (reliability, availability, maintainability, and safety) engineering: two scientific domains which have been historically considered separated. It was highlighted that hydrogen embrittlement is a complex degrading mechanism that results in detrimental effects on tensile properties, fracture toughness, and fatigue performance of a variety of metallic materials, and potentially in a loss of containment of hydrogen technologies. In this regard, inspection and maintenance activities must be carried out to preserve the physical integrity of components exposed to pure H_2 environments and maximize the system's safety and reliability, while minimizing operational costs. The RBI methodology, already well-established for the chemical and petrochemical sectors, is proven to be the most beneficial guideline for inspection planning in a variety of industrial sectors.

Despite this, the systematic review has highlighted how the RBI has been rarely adopted for components operating in hydrogenated environments, thus neglecting the detrimental effect of hydrogen embrittlement on the equipment's structural integrity. Inspections can be performed through non-destructive testing to effectively identify, monitor, and measure hydrogen-induced material degradation. Nevertheless, the major bottleneck for applying the RBI methodology to hydrogen technologies has a regulatory nature: at present, RBI standards and recommended practices do not consider HE a damage likely to occur. Hence, the utilization of the existing regulatory framework can lead to an inaccurate calculation of the probability of failure of hydrogen technologies, thus increasing the uncertainty to an unacceptable level when planning inspections.

The statistical analysis has shown an evident dearth of collaboration between the research groups from various countries and organizations with different expertise (i.e., material science and safety analysis). Considering this, it is advisable not only to strengthen the network between different nations and institutions but also to address the issue through a multidisciplinary approach. Future research projects on the operational safety of hydrogen technologies will benefit from the combined expertise in material science and risk analysis. Moreover, future versions of the RBI standards should include HE among the potential causes of material failure and develop a methodology to calculate the Damage Factor associated with this degradation. This amendment is essential to adopt the RBI methodology to plan inspection and maintenance activities for the emerging hydrogen infrastructure. The improvement of accident prevention policies is necessary not only for in-service equipment but also for components in the design phase, thus stimulating an increasingly widespread utilization of hydrogen in the forthcoming years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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