# Contribution to the definition of a partial overlapping plastic strain rates domain for moderate loadings - application to tensile testing on metallic materials

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**Abstract:** Generally, tensile testing on Hopkinson bars requires some particular considerations. Most of the specific devices, designed to hold tensile sheet specimens on the bars, involve the degradation of the pulses in particular case of no–direct tensile loadings. A tensile testing configuration for sheet specimens is proposed on the basis of classical split Hopkinson pressure bars (SHPB). Specimens holding is obtained with an epoxy adhesive and provides good measurements on sheet specimens.

A comparison is made for the same two metallic materials results extracted from literature and dynamic tensile tests performed with a high speed hydraulic machine and another split Hopkinson bars (SHPB) facility using hat-specimens. A partial overlapping domain in terms of plastic strain is shown at moderate strain rates from 200 to 400 $s^{-1}$

**Key words:** Sheet specimens, moderate strain rates, no–direct tensile loading, Hopkinson bars device, overlapping domains, metallic materials.

## NOTATION

| | |
|---|---|
| $\varepsilon$ | plastic strain (.) |
| $\dot{\varepsilon}$ | plastic strain rate ($s^{-1}$) |
| $\varepsilon_{eq}$ | equivalent plastic strain (.) |
| $\gamma$ | plastic shear strain (.) |
| $\sigma_{eq}$ | equivalent plastic stress (MPa) |
| $\sigma$ | conventional stress (MPa) |
| $\tau$ | duration time (ms) |

## INTRODUCTION

The identification of materials properties is based on the

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measurement of the evolution of the plastic stress/strain relations up to the fracture of the specimen over a large plastic strain rates range [0.0001;1000] $s^{-1}$. This range of strain and rates of strain is commonly observed during crash or impact of transportation frameworks. Consequently, thermoviscoplastic parameters of material laws, supplying FE models, have to be identified for the highest plastic strains through large experimental testing programmes. However, no universal facility allows to overlap this large range of strain and strain rates. The use of various testing facilities, bounded to partial strain rates ranges for a given plastic strain, is then necessary. Quasi-static machines, high–speed hydraulic machines and split Hopkinson bars are typically used as recurrent facilities. Technical limitations of high-speed hydraulic machines concern the exploitation capabilities of the collected raw data for a maximal plastic strain rate depending on the natural frequency of the assembly unit [1–3] and the closed loop control system. Moreover, the split Hopkinson bar technique is available for a limited time duration $\tau$ where the maximum strain is depending on the length and the

speed of the striker [4,5]. Deconvolution techniques have been recently developed [6,7] for lowest strain rates but are not yet commercially available. The paper proposes a tensile assembly unit composed of threaded sleeves for sheet specimens and placed between a split Hopkinson bars apparatus. The interest of the configuration lies in the minimisation of the impedance mismatch between the bars and the tensile assembly unit (see Fig. 3). The tensile loading is obtained indirectly by the impact of a long cylindrical projectile on the input bar in contact with the output bar. The dimensions of the bars and the location of the strain gauges are established with the help of a Lagrangian x/t diagram [8]. The influence of the fixing ends is evaluated to quantify the impedance mismatch. A tensile tests programme on two metallic alloys is carried out at moderate strain rates and compared to others tests results for the same metallic alloys obtained on a high-speed hydraulic machine [9] and a SHPB apparatus using hat-specimens [10].

## TESTING TECHNIQUE

### Description of the no-direct tensile testing configuration

The aim of the ductile materials characterization is to have a maximum duration time of the output bar's loading. For instance, a typical low carbon steel admits an ultimate engineering plastic strain close to 0.4 before fracture. Consequently, for a constant strain rate of 200 $s^{-1}$, the needed duration time $\tau$ is closed to 2 ms. To ensure such duration time pulses, a 5 m long projectile and a 10 m long input bar to ensure a correct separation of the pulses

without considering launch system limitations would be theoretically required. In order to ensure a maximum time duration of the incident pulse $\varepsilon_I(t)$ for our set-up – required for ductile materials – the length of the projectile is closed to 1.1 m.

For the corresponding duration time, thus 420 $s^{-1}$, an engineering plastic strain of 0.1 is obtained for a plastic strain rate equal to 250 $s^{-1}$ which is sufficient for the identification of behaviour laws parameters [11].

As represented in Figure 1, a Lagrangian x/t diagram illustrates the three elastic pulses propagation along the bars [8]. Considering the length of the projectile, the output bar (OB) is 2.7 m long which is necessary to avoid any superposition of the first reflected pulse with the incident one. The initial elastic pulse (bolded line) propagates along the joined bars and through the assembly unit. After being reflected at the free face of the output bar, the initial compressive incident wave becomes a tensile incident wave. The specimens are then loaded and, $e_I$ being known, usual complementary elastic pulses are then obtained ($\varepsilon_R$, $\varepsilon_T$). The location of the strain gauges was determined to avoid superposition of the reflected pulse $\varepsilon_R$ at the free ends with the incident pulse $e_I$ after its path along the two bars.

The no-direct tensile set-up is composed of two different bars lengths ($L_1$ and $L_2$) and a cylindrical projectile named $Lproj$ (see Fig. 2).

The two bars are made of 25 mm diameter maraging steel rods. The projectile is made of stainless steel with a 22.4 mm diameter. The Hopkinson bars are supported on 3 point-shapes spaced out 500 mm. The initial pulse is obtained from the impact of a cylindrical projectile
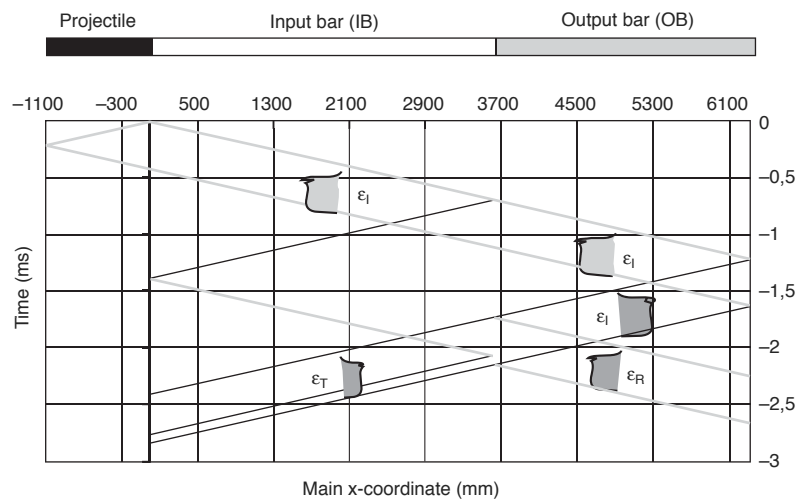


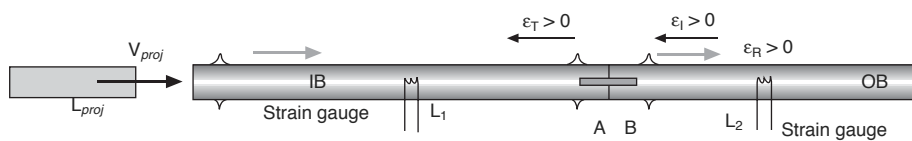*Figure 1* Lagrangian x/t diagram of no-direct tensile configuration on Hopkinson bars.



*Figure 2* Schematic diagram of the no-direct tensile loading.

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launched by a gas gun. The mechanical properties of the set-up is summarized in Table 1. The difference in diameter between the projectile and the bars induces a correction of the measured strain [12] in order to take into account the lack of energy brought back by the projectile.

*Table 1* **Specific dimensions of Hopkinson bars apparatus**

|  | L (m) | ∅ (mm) | Section (mm$^2$) | Density ρ (kg.m$^{-3}$) | Velocity C (m.s$^{-1}$) |
|---|---|---|---|---|---|
| input bar | 3.6 | 25 | 491 | 8198 | 4627 |
| output bar | 2.7 | 25 | 491 | 8171 | 4599 |
| projectile | 1.1 | 22.4 | 394 | 7702 | 5288 |

The three elastic pulses ($\varepsilon_I(t)$, $\varepsilon_T(t)$ and $\varepsilon_R(t)$) are recorded with a set of 3.2 mm strain gauges CEA-06-125-UN-350 (ref. Measurement group) bonded on the Hopkinson bars with a cyanoacrylate adhesive. The output signals are obtained from a full-bridge into a Vishay 2310 amplifier. A 8-channel transient recorder (Nicolet MultiPro – sampling rate 1 MHz) is used to storage tests data (elastic pulses and signals from photo-diodes) afterwards. The length of the strain gauge allows a 145 kHz bandwidth whereas a typical spectral signature of an impact using bars is closed to 50 kHz. The length of the cylindrical bars, the location of the strain gauges and the gauge dimensions of the specimen have been determined using classical relations [12, 13].

## TENSILE TESTS RESULTS

### Material and specimens preparation

Many modifications for the fixation of the specimens onto the bars are generally provided to ensure the holding of both undeformed parts on the specimen. For this, an adaptive assembly must be designed to produce a solicitation as pure as possible. The holding of the specimen is usually made with pin attachments (for plate specimens) or threads (for axi-symetric specimens). Those modifications may induce an impedance mismatch because of cross section variations in the bars [8, 14–16] or in the assembly [17–19]. Any section variation must be taken into account for the waves analysis [14]. For the proposed assembly unit, the two sleeves have been machined from the same steel alloy as the cylindrical bars by wire electro-erosion. The choice of the principle is based on the minimization of the impedance mismatch [10, 15, 18, 20].

The speed of the striker bar has been limited to 10 m.s$^{-1}$ to avoid strain gauges deterioration. Moreover, the lowest speed is closed to 3 m.s$^{-1}$ considering the limitations of the launching system. The gauge length for sheets specimen is chosen close to 11.3 mm. It allows to reach the moderate strain rates domain [200;700] s$^{-1}$ for tensile tests. The full section is equal to four gauge sections of a specimen in order to obtain a significant amplitude of the transmitted signal and to avoid its amplification. The cross section of the sleeves is slightly decreased (2%) by the four grooves tooled on the cylindrical sleeves surfaces for the positioning of the specimens (see Fig. 3). The gauge lengths of the specimens lies between 6.8 and 25 mm to have access to a theoretical strain rates range from 120 to 1400 s$^{-1}$. For the lowest rate of strain, plastic strains close to 0.05 are measured. In the same way, the current set-up allows to reach plastic strains up to fracture for higher strain rates according to (1).

$$\varepsilon = \dot{\varepsilon} \cdot \tau \qquad [1]$$

Figure 3 illustrates the progress of the 4–glued sheet specimens on the sleeves. An epoxy adhesive is laid on the adhesive areas of the specimens. Then, a pre-load is done at the free faces of the unit assembly to avoid any gap between the sleeves after the polymerisation of the epoxy adhesive (12 hours at room temperature).

Figure 4 shows the typical records on each bar using the no-direct tensile configuration on sheet specimens.

### XES steel and 2024 T3 aluminium alloy material characterization

Tensile specimens have been machined by wire electro-erosion from a cold-rolled sheet of XES steel (*Wt%* C = 0.05–Cr < 0.01–Cu = 0.013–Mn = 0.018–Al = 0.064–Ni = 0.02) and 2024T3 aluminium alloy (*Wt%* Al = 93.5–Zn = 0.22–Mg = 1.4–Cu = 4.2–Mn = 0.48–Fe = 0.17–Si = 0.07). The XES steel specimens were machined from a 1.17 mm thick plate and oriented in the rolling direction. The 2024 T3 aluminium alloy specimens were machined from a 1 mm thick plate and oriented at 90° regarding the rolling direction. Conventional quasi-static tests (QS) on the same geometry have been performed using an Instron universal testing machine (Model 1195) at a constant cross speed of 5 mm.min$^{-1}$. Oscillations are observed for the highest plastic strain rate close to 420 s$^{-1}$ and perturbs the stress vs. time calculation (see Fig. 5). The oscillations
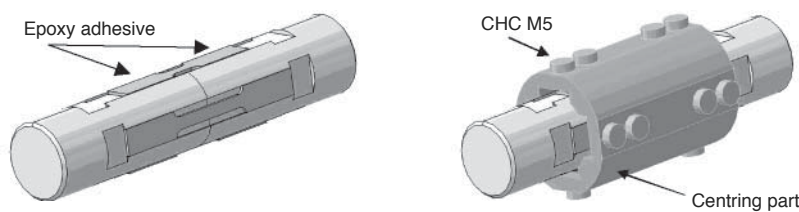


*Figure 3* Progress of the 4-sheet metallic specimens on the cylindrical parts.
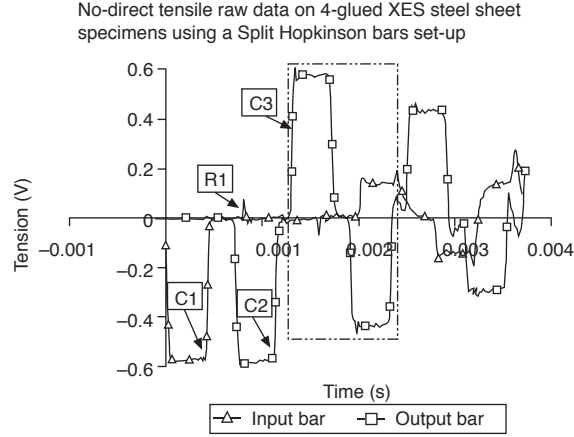
Figure 4 Raw data under no–direct tensile tests on Hopkinson bars device.

period corresponds to the run inside the sleeves of a partial reflected pulse of the incident wave. These interfaces may be responsible of the various reflections in the system [21]. So, the comparison is made considering filtered data (low frequency pass filtering) for impact tests using Hopkinson bars [22]. The input/output forces balance has been previously cheeked [21]. For further comparisons between the various dynamic facilities, the tests made with
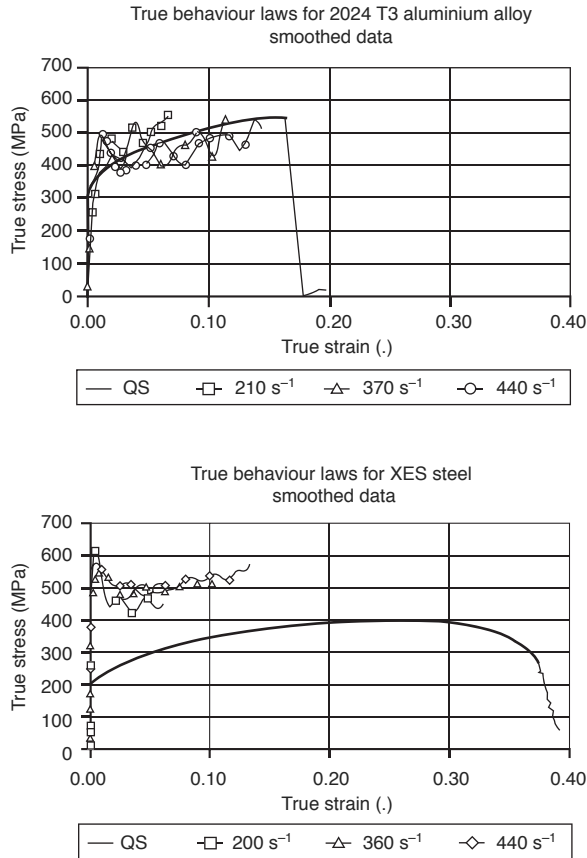




Figure 5 Behaviour laws at various strain rates – 2024 T3 aluminium and XES steel.

the proposed configuration on the split Hopkinson bars apparatus are called "No-direct SHB".

**Comparison for different testing devices**

Two others testing facilities were used to complete the considered range in terms of strain and rates of strain. This approach is generally led to encompass a large strain rate domain [23–25]. A hydraulic Schenck machine uses a 50 kN capacity linear actuator (see Fig. 6).
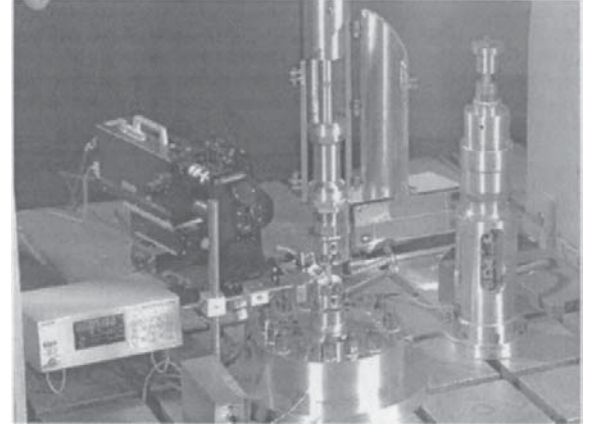


Figure 6 High-speed hydraulic testing machine (Onera–Lille Centre).

For the present tests, the servo system was programmed with a ramp function to provide a constant relative jack speed available up to $4\,\mathrm{m.s^{-1}}$. Previous works have permitted to through out the natural frequency of the assembly. This kind of device is naturally subjected to mechanical vibrations depending on the weight of the added mass and the stiffness of the piezo-electric load cell [1–3, 9]. The natural frequency of the testing set-up is closed to 8 kHz which allows the access to theoretical plastic strain rates close to $200\ \mathrm{s^{-1}}$ according to material properties of the considered alloy [9, 26]. The mechanical oscillations correspond to the natural frequency of the set-up due to the dynamic loading of the specimen and remains when fracture occurs [23]. For the tests on the hydraulic testing machine, an optical extensometer (Zimmer XH 200) was employed to measure higher plastic strains [26]. The gauge length L1 of the specimen was taken equal to 6.8 mm for a higher strain rates range [27, 28].

The second facility is composed of a SHPB apparatus described in details by Mouro [10] (see Fig. 7). In that configuration, a hat-specimen – machined by wire electro-erosion and folded by a quasi static machine – is placed into a specific assembly unit between two cylindrical maraging bars (see Fig. 8).

The behaviour laws obtained using the high-speed hydraulic machine are named "H" and presented in details by Haugou [26]. In the same way, the tests results obtained with the second split Hopkinson pressure bars are named "SHPB-LMS". The results are plotted for the different testing devices and measurement systems (see Figs. 9 and
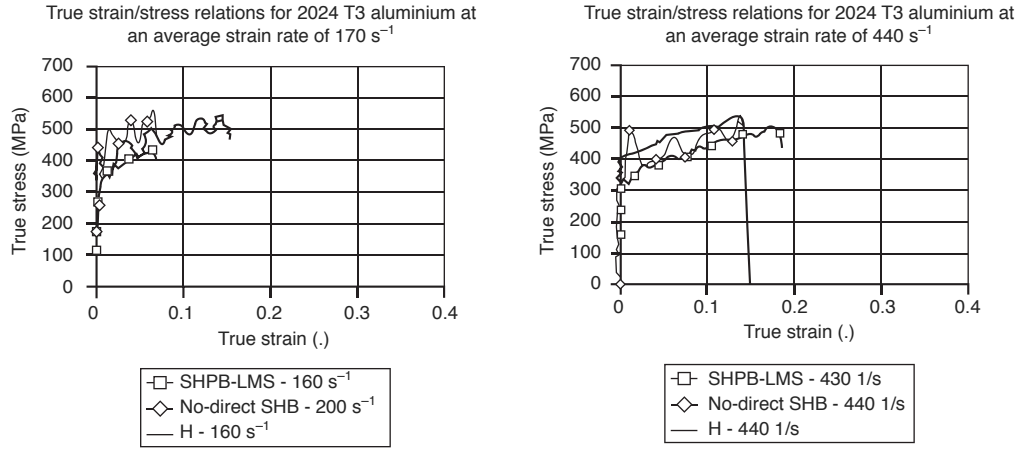
*Figure 7* Special supports on classical SHPB (LMS–Polytechnique).

10). The comparison is done for the XES low carbon steel at average strain rates of 230 and 520 s$^{-1}$. In the same way, the comparison of the true relations is done for the 2024 T3 aluminium alloy and the same testing devices. It is verified that the considered alloy is not strain rate sensitive from quasi–static rates of strain to 500 s$^{-1}$ (see Fig. 10).

**OVERLAPPING DOMAIN – DISCUSSION**

The comparison is made with results of previous tests

programmes carried out for the 2024 T3 aluminium alloy [11, 27]. Nicholas and Lawson [27] have performed shear tests from 10$^{-4}$ to 4500 s$^{-1}$ using three different testing devices (see Fig. 11). A quasi–static machine has covered the range of strain rates [10$^{-4}$;10$^{-2}$] s$^{-1}$. A pneumatic machine has been used for the next domain from 10$^{-2}$ to 100 s$^{-1}$. Stress/strain relations from 500 to 4500 s$^{-1}$ have been obtained with a torsional Hopkinson bars device. Plastic shear stress have been converted according to classical relations (2) and (3) based on the von Mises flow rules [29]. Langrand [11] has made quasi–static and dynamic tensile tests from 0.003 to 55 s$^{-1}$ in order to identify the parameters of Johnson-Cook model for the 2024 T3 aluminium in order to supply FE riveted aeronautic frameworks models. The present comparison shows a good agreement with results obtained with the no–direct tensile configuration. The present testing process is then validated.

$$\sigma_{eq} = \sigma = \tau \cdot \sqrt{3} \qquad [2]$$

$$\varepsilon_{eq} = \varepsilon = \frac{\gamma}{\sqrt{3}} \qquad [3]$$

For the XES steel, previous tests programmes have



*Figure 8* Geometry and dimensions of hat specimens (mm).



*Figure 9* True relations of XES steel from different testing devices.

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**True strain/stress relations for 2024 T3 aluminium at an average strain rate of 170 s⁻¹**

Legend:
- SHPB-LMS - 160 s⁻¹
- No-direct SHB - 200 s⁻¹
- H - 160 s⁻¹

**True strain/stress relations for 2024 T3 aluminium at an average strain rate of 440 s⁻¹**

Legend:
- SHPB-LMS - 430 1/s
- No-direct SHB - 440 1/s
- H - 440 1/s

*Figure 10* True relations of 2024 T3 aluminium alloy from different devices.



**Evolution of the 0.1 engineering stress versus strain rate - 2024 T3 aluminium alloy**

Legend:
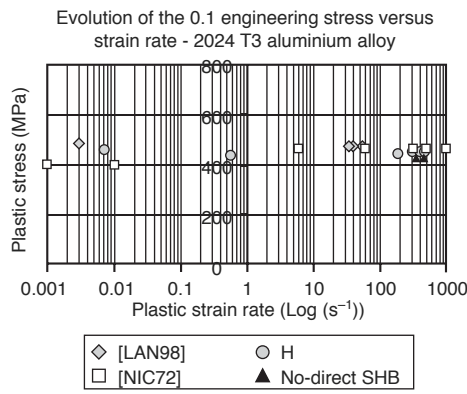- [LAN98]
- [NIC72]
- H
- No-direct SHB

*Figure 11* Comparison of the 0.1 plastic stress – 2024 T3 aluminium alloy.

been prospected under double shear [22], compression [5] and tensile [10] tests on sheet specimens within split Hopkinson bars devices. The domain of plastic strain rates was about 100 to 900 s⁻¹. Materials are revealed to be strain rate sensitive for these various tests programs and the considered steel alloy, particularly for strain rates up to 100 s⁻¹ (see Fig. 12). However, the use of different
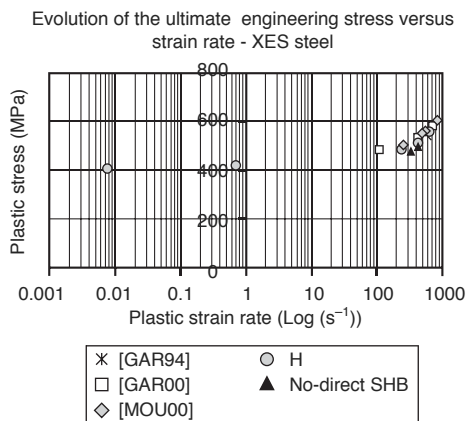
testing facilities raises the problem of the interpolation of the mechanical properties identified close to the technological limits of each device, such as oscillations on high–speed hydraulic machines and limited time duration on Hopkinson bars.

On the basis of the present tests programme, an overlapping domain is established for moderate rates of strain using plate specimens made of the same metallic alloys. The classical measurements devices have put into evidence a discontinuous plastic strain domain for moderate strain rates. This is especially clear for strain rate below 500 and 700 s⁻¹ respectively for the 2024 T3 aluminium alloy and XES steel (see Figs. 13 and 14). So, for FE modelling of frameworks submitted to large plastic strains and plastic strain rates, an unknown domain remains to correctly identify parameters of viscoplastic laws.
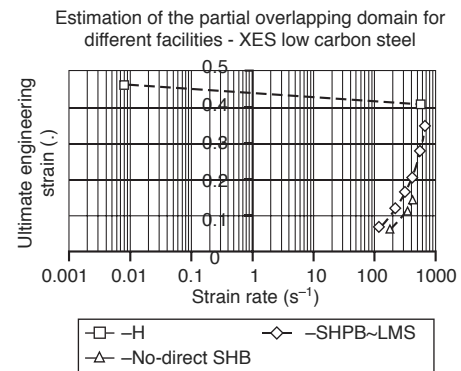


**Estimation of the partial overlapping domain for different facilities - XES low carbon steel**

Legend:
- –H
- –SHPB~LMS
- –No-direct SHB

*Figure 13* Overlapping domain for different testing facilities – XES steel.

### CONCLUSIONS

The paper presents a no–direct tensile testing configuration based on glued sheet specimens on cylindrical sleeves. This assembly unit – containing 4–glued sheet specimens on its external surfaces without any others attachment tools – is threaded on a split Hopkinson bars device. Nevertheless, a problem of oscillations is still to be solved
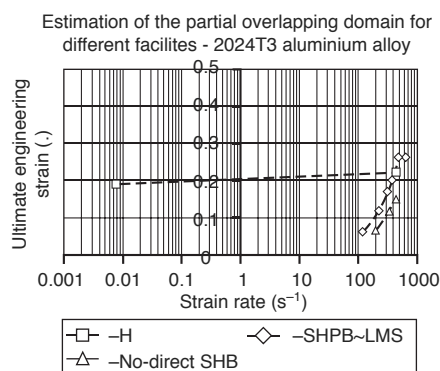


**Evolution of the ultimate engineering stress versus strain rate - XES steel**

Legend:
- [GAR94]
- [GAR00]
- [MOU00]
- H
- No-direct SHB

*Figure 12* Comparison of the ultimate plastic stress – XES steel.

*Figure 14* Overlapping domain for different testing facilities – 2024 T3 aluminium alloy.

to allow classical SHPB processing of the raw signals. Moreover, the gluing progress have to be controlled to avoid detachment for high strength materials (*i.e.* composites, HSS). This involves particular care for the design of the specimens and the related strain rates ranges.

The comparison of results obtained using the proposed no-direct tensile solicitation using classical Hopkinson bars apparatus with results from others techniques is shown for a common strain rates range from 200 up to 400 s$^{-1}$. A high-speed hydraulic machine and a SHPB apparatus using hat-specimens are used for this purpose in order to have access to the domains of plastic rates of strain [0.002; 500] s$^{-1}$ and [120; 700] s$^{-1}$, respectively. A good agreement is observed for the engineering stress/strain relations provided by the different tests facilities. A restricted overlapping domain has been underlined for the moderate plastic strain rates [120; 500] s$^{-1}$ and plastic strains up to 0.1 for both metallic alloys (2024 T3 aluminium alloy and XES low carbon steel). This constitutes a limitation for FE analysis of crashworthiness behaviour in particular case where fracture is observed.

Then, direct measurements for the analysis of plastic strains using no-contact measurement devices are considered as optical extensometer techniques, high-speed camera for correlation analysis. In these conditions, a direct tensile configuration on SHB is required using the proposed assembly unit.

## ACKNOWLEDGMENTS

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