Multidirectional bender element measurements in the triaxial cell: equipment set-up and signal interpretation

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Summary

The paper presents a description of the arrangements of the vertical and horizontal bender elements and their implementation in stress-path triaxial cells, together with the comparison among three of the most commonly used interpretation methods of the bender elements signals to identify the travel time of the input wave to the receiver. The methods are the first arrival time, travel time between the characteristic points, cross-correlation method and π-point phase comparison method. For the material tested in this research and the test boundary conditions, the signals from bender elements demonstrate that the travel time should be taken as the time corresponding to that obtained by the first arrival method based on the visual identification of the wave arrival to the receiver. The horizontal and vertical bender elements implemented in stress-path triaxial cells have been used to investigate the evolution of shear moduli $G_{ij}$ of reconstituted specimens of Lucera clay (Southern Italy) under both isotropic and anisotropic stress states up to pressures higher than those usually achieved in similar studies. In this way the influence of long anisotropic stress paths on the clay stiffness will be highlighted. It is deduced that the different plastic straining resulting from the imposition of different virgin radial paths tends to modify the original pattern of $G_{ij}$.

Keywords: laboratory test, bender elements, travel time, small strain shear stiffness.

1. Introduction

Nowadays the use of the bender element technique to measure very small strain shear stiffness of soils in the laboratory is well established, since it is recognized to allow for reliable and relatively economical shear wave velocity measurements during oedometer [e.g. DYVIK and MADSHUS, 1985; JAMIOLKOWSKI et al., 1995; FAM and SANTAMARINA, 1995; KAWAGUCHI et al., 2001] and triaxial tests [e.g. VIGGIANI and ATKINSON, 1995a,b; BRIGNOLI et al., 1996; JOVIČIĆ and COOP, 1998; PENNINGTON et al., 1997, 2001].

In the bender element test, the time ($T$) of propagation of a shear wave through the soil specimen is measured. Assuming that strains transferred by the bender element to the soil are small enough to excite the material in its elastic range and knowing the current tip to tip distance, $L_a$, between the elements, the velocity of the shear wave, $V_s$, and the very small strain shear modulus $G_{\text{max}} = G_0$ are determined as:

$$V_s = \frac{L_a}{T} ; \quad G_{\text{max}} = \rho V_s^2 \quad (1)$$

where $\rho$ is the density of the soil. Although, in principle, the use of bender elements appears to be straightforward, in practice the interpretation of the test results can lead to uncertain findings, due to the difficulty in identifying the exact travel time of the shear wave [e.g. VIGGIANI and ATKINSON, 1995a; BRIGNOLI et al., 1996; JOVICIC et al., 1996; ARULNATHAN et al., 1998; ARROYO et al., 2003; GREENING and NASH, 2004; LEONG et al., 2009].

The bender elements equipment and installation technique have evolved significantly in the last two decades [e.g. DYVIK and MADSHUS, 1985; FAM and SANTAMARINA, 1995; BRIGNOLI et al., 1996; Jovičić and Coop, 1998; PENNINGTON et al., 2001]. This evolution has also been complemented by a number of research works aimed at improving the objectivity and repeatability of the interpretation methods [e.g. MANGILO et al., 1989; BRIGNOLI et al., 1996; Jovičić et al., 1996; BLEWETT et al., 2000; GREENING and NASH, 2004; LEE and SANTAMARINA, 2005; LEONG et al., 2005, 2009]. However, the correct interpretation of the signals is still an open issue and far from being fully standardised, due to the intrinsic complexity of the wave propagation process within the specimen during the laboratory test and to the distortion of the wave during its travel.

This paper presents the setting-up and use of a recently developed bender element installation de-
signed for the measurement of the evolution of the stiffness anisotropy of a reconstituted clay when subjected to different consolidation histories. The paper mainly focuses on a critical comparison among three different procedures of analysis and interpretation of the bender element test data: namely the first arrival method, time between the characteristic points, the cross-correlation method and the π-point phase comparison method. The aim of the comparison is to highlight the merits and limitations of such methods with particular reference to the use of bender elements in the investigation of the cross-anisotropy of clayey materials.

2. Experimental background and research aims

In the context of very small strain behaviour, the response of soils can be assumed as reversible. For cross-anisotropic elastic materials, the set of independent elastic parameters that relates the effective stress increments, $\Delta \sigma_{ij}$, to the strain increments, $\Delta \varepsilon_{ij}$, is: $E'_v, E'_h, \nu_{vh}, \nu_{hh}$ and $G_{vh}=G_{hv}$ [LOVE, 1927], where, for the shear moduli $G_{ij}$, the subscripts $ij$ define the plane in which shearing occurs and the direction of shearing, respectively. With reference to the above set of parameters, $G_{hh}$ can be expressed as a function of $E'_h$ and $\nu_{hh}$.

The independent measurement of $G_{hh}, G_{hv}$, and $G_{vh}$ during a controlled stress path test can be used to investigate the cross-anisotropic elasticity of a clay specimen. Within the conventional arrangement of bender elements in a triaxial system, vertical elements are fitted in both the top and base rigid platens [DYVIK and MADSHUS, 1985]. This configuration allows solely for the measurement of the stiffness modulus $G_{vh}$. It has been used in several research works devoted to the investigation of the dependence of $G_{vh}$ on the mean effective stress, $p'$, the clay overconsolidation ratio, $R$ [VIGGANI and ATKINSON, 1995b], and the stress ratio $\eta=q/p'$ [e.g. RAMPELLO et al., 1997].

Since the setting-up of horizontal bender elements in the triaxial cell, the anisotropic small strain stiffnesses of clay and the dependence of $G_{hv}$ and $G_{hh}$ on $p'$ and $R$ [e.g. PENNINGTON et al., 1997; JOVICIĆ and COOP, 1998; NASH et al., 1999; PENNINGTON et al., 2001] have been also investigated. In particular, the stiffness anisotropy has been investigated by comparing $G_{vh}$ with $G_{hh}$. However, the published results giving evidence to the cross-anisotropic features of clays are limited [e.g. JANIOLEKOWSKI et al., 1995; Jovicic and Coop, 1998; Nash et al., 1999] and refer solely to tests carried out at relatively moderate stress levels. Given so, they do not fully assess the evolutive character of both stiffness moduli, $G_{hv}$ and $G_{hh}$, and of the stiffness anisotropy with stress ratio and plastic straining, which could be investigated only through testing the soil within a relatively large pressure range. In addition, the measurement of both $G_{hv}$ and $G_{hh}$ at the same time on a single triaxial specimen during a controlled stress path test is desirable when assessing elastic cross-anisotropy. To this purpose, PENNINGTON et al. [1997] proposed horizontal bender elements specifically designed to measure $G_{hv}$ and $G_{hh}$ at the same time. Similar horizontal bender elements were constructed and used in the research work referred to in this paper, according to a programme designed to investigate the variation of both $G_{hv}$ and $G_{hh}$ of reconstituted clay when subjected to either isotropic or anisotropic loading. In particular, the bender element tests were carried out on a reconstituted clay consolidated one-dimensionally up to a nominal vertical effective stress of about 100 kPa and subjected to further consolidation under different stress ratios. The effective stresses reached during testing were larger than those reached in previous research works [e.g. RAMPELLO et al., 1997; NASH et al., 1999; PENNINGTON et al., 2001] and sufficient to induce significant plastic straining leading to different evolution of the shear stiffness moduli along differently oriented consolidation radial paths.

3. Laboratory testing equipment

The tests discussed in this paper were carried out, on 76 mm height, 38 mm diameter specimens of reconstituted Lucera clay, in two computer-controlled stress-path cells of the type described by TAYLOR and COOP [1993]. These are equipped with both conventional and advanced instrumentation. In fact, the cells are fitted with local axial strain measurement transducers, which are either electrolevel type transducers [JARDINE et al., 1984] or submersible linear variable differential transformers, LVDT [GUCCOVOLI and COOP, 1997]. The cells are also equipped with both vertical and horizontal bender elements (Fig. 1).

As originally reported by DYVIK and MADSHUS [1985], piezo-ceramic bender elements are electro-mechanical transducers capable of converting mechanical energy (movement) either to or from electrical energy. A bender element typically consists of two thin conductive piezo-ceramic plates rigidly bonded to a central metallic plate. When a driving voltage is applied to the element, one plate elongates and the other shortens resulting in the bending of the system (Fig. 2) [e.g. DYVIK and MADSHUS, 1983; BRIGNOLI et al., 1996]. Similarly, when the element is forced to bend, the deformation imposed to the conducting layers results in a measurable electrical signal. The bender bimorph elements used in
this project are made of piezoelectric ceramic (lead zinconate titanate), with brass as central metallic plate. They were manufactured and cut to a size of 13×10×0.6 mm for the vertical bender elements and of 16×6×0.6 mm for the horizontal ones. Bender elements are connected either in series or parallel. The series version performs better as a receiver, that is, for a given distortion it generates a higher output than the parallel version. Such higher output develops because the voltage is equal to the sum of the potential differences available at the electrodes of each ceramic element.

With the parallel version the available voltage is applied across each ceramic plate; such version is typically adopted for the transmitter bender, because it provides the largest distortion as response to the application of any given input voltage. In fact, the element with series connection of the electrodes will produce twice the voltage variation of the parallel connection element for any given distortion, whereas the element with parallel connection will produce twice the displacement of the element with series connection, for any given input signal [e.g. Dvirk and Madshus, 1985; Brignoli et al., 1996]. Therefore, although it can be difficult to set a parallel connection, adopting this latter for the transmitter bender element, along with a series connection for the receiver bender element, improves the quality of the received signal [Leong et al., 2005]. In order to prevent the elements from short-circuiting when in contact with water, they have to be coated with a waterproof epoxy resin (Araldite MY753 mixed with 10% HY951 hardener).

Details about the bender element construction and implementation in the triaxial apparatus carried out in this work are discussed in the following sections. A programmable TG1010A 10 MHz DDS function generator was connected to the transmitter bender element to produce the input signal, whereas an oscilloscope Tektronix TDS 3014B was used for the wave data acquisition (Fig. 1). This oscilloscope has four recording channels and a maximum sampling rate of 1MHz. The data recorded by the digital oscilloscope were transferred to the computer for further signal processing.

3.1. Vertical bender elements

Some modifications of the pedestal (Fig. 4), top cap (Fig. 5) and triaxial base were required to accommodate the vertical bender elements and corresponding cables in the triaxial cell and to prevent leakage from both the cell water and the pore water circuits.
The vertical bender element (13×10×0.6 mm) arrangement was developed according to the design reported by Dyvik and Madshus [1985]; it consists of an epoxy-cased element (Fig. 3) placed into a pressure-proof cylindrical brass plug (Fig. 4c). This plug is placed into the triaxial pedestal (Fig. 4) or in the top cap (Fig. 5). In the present research work one of the pedestals was made of brass and the other one of galvanized aluminium, whereas both the top caps were made of Perspex; however, the procedure to accommodate the bender elements was the same for all pedestals and top caps.

The brass plugs have a slot in the centre where the bender element is placed, as shown in figure 4c. This slot is filled with epoxy resin to create a rigid fixture and to isolate the wire and connections from water. The bender elements are mounted so that 11 mm of the total length of the element are embedded into the resin and the rest protrude into the specimen (3 mm, cantilever length, \(L_b\)). In this work it was chosen to use plugs, instead of slots, set in either the pedestal or the top cap, because they can be replaced without changing the pedestal and the top cap, if the bender element breaks down.

A bronze porous stone of coarse-medium grain size was placed onto the platen of the pedestal (within a corresponding circular slot) and below the top cap (Fig. 4d).

The wires run through holes crossing the plug, the pedestal, the triaxial base and the top cap. Highly flexible PTFE (Politetrafluoroetilene) coaxial cables were used to ensure isolation of the cell water and to provide an efficient noise shield in the cell. This type of cable is covered with a heat shrinking sleeve, in order to avoid any water infiltration. The PVC (Polyvinyl-Chloride) coaxial cables were used to ensure an efficient noise shield outside the cell. The connections between the copper wires (which are covered with a rubber sleeve) and the PVC cable were located within the pedestal; the PVC cables exit the pedestal and base holes (Fig. 4a). At the pedestal base, the wiring system was as sketched in figure 4b, such that the connection between the PVC cable and the copper wires was not influenced by movements of the PVC cable.

Also for the top cap, the copper wires were covered with a rubber sleeve and the connection between these wires and the PTFE cable were located inside tube 2 (Fig. 5a,b). The PTFE cable exits the cell through a pressure-proof plug (Fig. 5c), inside which were the connections with the PVC cable. All joints between cables and tubes are covered with an adhesive heat shrinking sleeve (Fig. 5b). In this case the wire blocking system was inside the pressure-proof plug and was achieved by means of a plate screw. The isolation of such system from the cell water (between tube 1 and tube 2 and between tube 2 and the top cap) was ensured by the use of loctite. The plugs, triaxial cell and electrical instruments were all properly grounded, in order to make sure that no ground loops occurred.

3.2. Horizontal bender elements

Similarly to the vertical elements, the horizontal piezo-ceramic elements were coated with a highly water-resistant epoxy resin. Based on the design of Pennington et al. [1997; 2001], two elements (16x6x0.6 mm) were embedded into a resin-filled brass hollow cylinder, 17 mm long and of 12 mm diameter (Figs. 6, 7). The two piezo-ceramic elements were placed perpendicular to each other, so that two orthogonal shear waves could be triggered (travelling in the horizontal direction, but with either horizontal or vertical particle movement). Therefore, the brass-resin-cylinder probe served both as a protective coating for the connections between the PTFE cable and the transducer plate and as grounding. In fact, the red copper wire, which can be seen in figure 7, was soldered onto the inner surface of the brass cylinder, which acted as grounding for the horizontal bender element. The brass hollow cylinder was filled with
epoxy resin. Only 4 mm length of the element protruded outside the resin probe (cantilever length, \(L_b\)).

For the horizontal elements, the pressure-proof plugs (Fig. 5c) similar to those used for the vertical bender elements, were used for lodging of the connection between the PTFE cable (covered with heat shrink sleeve) and the PVC cable. At the end of each PVC cable, BNC connectors were used to connect the bender elements to the function generator and the oscilloscope.

Latex grommets were sealed around two holes at mid height of the latex membrane for installation of the horizontal bender elements’ plug (Fig. 8 a,b), according to the procedure suggested by GASPARRE [2005]. Three layers of liquid latex were applied to an on-purpose made mould to make these latex grommets. Once the horizontal bender elements were pushed into the specimen through these grommets, an o-ring was installed on each grommet and two additional layers of liquid latex were applied in order to seal the system (Fig. 8c).
4. Material tested and experimental programme

The material tested has been the reconstituted Lucera clay. This clay is part of the Sub-Apennine Blue Clays outcropping on the hill-slopes below the town of Lucera that is located in Northern Apulia (Southern Italy; Fig. 9). The soil is a medium plasticity clay (IP = 24-25%), possessing a clay fraction (CF) of about 45% [MITARITONNA et al., 2008].

The clay was reconstituted in laboratory following the procedure reported by BURLAND [1990]. The slurry (of water content 1.5wL=70%) was one-dimensionally compressed in a consolidometer, with incremental loading up to a nominal vertical effective stress of 100 kPa.

The critical state stress ratio of reconstituted Lucera clay, $M^*$, has been measured in triaxial tests to be about 1.08, with corresponding critical state angle of shearing resistance $\phi^*_c = 26^\circ$. Therefore, the earth pressure coefficient at rest, $K_0$, of reconstituted normally consolidated Lucera clay, if deduced according to the expression by JAKY [1944], $K_0=1-\sin\phi^*_c$, would be equal to 0.56 and the corresponding stress ratio, $\eta = q/p'$, would equal 0.6. In the following section, this value is considered to be the stress ratio characterizing the loading path which the clay was subjected to during normal consolidation in the consolidometer.

The testing programme discussed in the present work was designed to investigate the evolution of small strain shear stiffness of reconstituted clay under either isotropic or anisotropic loading conditions, up to mean effective stresses, $p'$, about twenty times larger than those reached in the consolidometer. To do so, constant-$\eta$ stress path tests were carried out on specimens trimmed from the reconstituted sample extruded from the consolidometer in undrained conditions. Each specimen was trimmed using sharp knives, to a size slightly larger than the standard one: 76×38mm. A maximum time of 30 minutes was spent to prepare the specimen, in order to avoid significant drying. As the reconstituted specimens were initially soft, the bender elements were pushed directly into the specimens, so that the contact conditions between bender elements and soil were optimal. For all the specimens trimmed as described above, the presence in the clay of a suction of about 20 kPa was detected by undrained isotropic loading at the start of testing. A similar suction value was also measured on the same material by means of the filter paper technique [e.g. CHANDLER and GUTIERREZ, 1986]. Therefore, such undrained loading was followed by an isotropic consolidation at $p'=20$ kPa. Table I and figures 10 and 11 report the different stress path tests which were carried out on the clay specimens after consolidation at $p'=20$ kPa. All the specimens were first com-
pressed isotropically from $p' = 20$ kPa to $p' = 70$ kPa, and then they were either further compressed isotropically or brought to values of the stress ratio $\eta = q/p'$ equal to: 0.3, 0.6 and 0.8, along constant-$p'$ paths (Figs. 10, 11).

Specimen 1 was isotropically ($\eta = 0$) consolidated up to $p' = 1350$ kPa (Figs. 10, 11). Specimens 2 and 3 were both isotropically consolidated up to $p' = 70$ kPa and then brought, along constant-$p'$ paths, to stress ratios $\eta = 0.3$ and $\eta = 0.6$ respectively; thereafter they were anisotropically consolidated up to $p' = 1350$ kPa. Unloading-reloading stages were carried during both tests 2 and 3; specimen 2 was swelled from $p' = 350$ kPa to $p' = 175$ kPa and then reloaded along the virgin compression line (Figs. 10, 11). Specimen 3 was swelled from $p' = 350$ kPa to $p' = 70$ kPa and from $p' = 1350$ kPa to $p' = 350$ kPa. Specimen 4 was isotropically consolidated up to $p' = 70$ kPa, then brought to the stress ratio $\eta = 0.8$ along a constant-$p'$ path, then anisotropically consolidated up to $p' = 700$ kPa; thereafter it was brought, along a constant-$p'$ path, to the stress ratio $\eta = 0.1$ and consolidated at constant $\eta$ up to $p' = 1350$ kPa (Figs. 10, 11). Specimen 5 was isotropically consolidated up to $p' = 350$ kPa and brought to the stress ratio $\eta = 0.8$ along a constant-$p'$ path, but it was then consolidated at $\eta = 0.8$ only up to $p' = 350$ kPa. Thereafter, it was brought to the stress ratio $\eta = 0.1$ at constant-$p'$ and was then consolidated, at constant $\eta$, up to $p' = 1240$ kPa (Figs. 10, 11 and Tab. 1).
10^{-11} \text{ m/s}, and a value of the coefficient of one dimensional consolidation \( c_v \) equal to 1.6 E-08 m/s². However, loading was stopped at \( p' \) equal to: 20, 70, 175, 350, 700, 1350 kPa in order to allow for the dissipation of any unpredicted excess pore water pressure, which had eventually developed during the preceding stage of constant loading rate, and also to allow for creep. Each consolidation and creep stage was stopped when the volumetric strain rate dropped below 0.05 %/day. Hereafter, the final states of the consolidation-creep stages will be called “equilibrium states”. Figure 11 shows, in the specific volume, \( \nu \), logarithm of mean effective stress, log \( p' \), plane, the equilibrium states and the corresponding compression and swelling curves for the tests shown in figure 10. The compression curves represent the different normal-consolidation lines corresponding to the different stress ratios, \( \eta \). The curves are nearly parallel straight lines, with an average gradient \( \lambda = 0.14 \). The gradients \( \kappa \) of the swelling line are all approximately about 0.026. The compression curves of both tests 4 and 5 (Fig. 11) tend towards the isotropic normal-consolidation line after the drop of \( \eta \) from 0.8 to 0.1.

The shear stiffnesses were measured by means of bender elements at each equilibrium state. In the following, the different analyses of the bender element test data according to the above mentioned different methods are discussed.

5. Bender element tests: measurements and interpretation procedures

A preliminary compliance testing of all the bender elements used in this work was carried out in order to account for the delay in estimating the travel time through the soil due to the electronics, the ceramics and the coating materials. Such compliances were assessed by placing the two bender element platens in contact as suggested by Brignoli et al. [1996] and Pennington et al. [2001], and by measuring the time interval \( (t_c) \) between the input and the output wave. For each pair of bender elements a time delay in the range of 5 μs was measured. All \( G_{ij} \) measurements have been then corrected accounting for this time delay. This systematic error introduces a bigger error for the shear wave velocities measured by means of the horizontal bender elements than for those deduced according to the vertical ones, due to the different travel distances. In particular, the error in \( V_{vh} \) measurement is estimated to be about 1%, whereas for \( V_{bh} \) and \( V_{hv} \) is of the order of 2.5%. These errors have been estimated during bench tests carried out on reconstituted Lucera clay specimens of 76 mm × 38 mm.

Methods to interpret the bender element signals share parallels with geophysical techniques used in the field, such as cross-hole and down-hole tests. As with these techniques, shear wave velocity has usually been derived from the direct measurement of the travel time of the wave front that can be
detected by the recognition of the first arrival of the wave at the receiver. However, some weaknesses have been recognised to characterise this time domain method. Sánchez-Saliner et al. [1986] showed that a rapidly attenuating shear wave, that propagates with the velocity of a compression wave, generally accompanies the shear wave, this phenomenon being defined as a near-field effect. In addition, the paths followed by the waves from transmitter to receiver are often not straight. For example, in the case of vertical bender elements set-up in the triaxial apparatus, non-straight paths appear to result from reflection phenomena between the top and bottom platens of the triaxial cell [Arulnathan et al., 1998]. Arroyo et al. [2003; 2006] found that specimen size has an effect on the received signal in bender element tests, due to reflection from the boundary of the specimen. This effect is more pronounced in small-diameter soil specimens. The effects of these and possibly other factors often could make the recognition of the first arrival of the wave at the receiver particularly difficult. Thus, several alternative techniques, such as the cross-correlation technique [Sánchez-Saliner et al., 1986; Mancuso et al., 1989], the use of customized input signals [Jovičić et al., 1996], or methods developed in the frequency domain, such as the π-point phase comparison method [Kaarsberg, 1975; Sachse and Pao, 1978; Blewett et al., 2000; Greening and Nash, 2004], have been proposed in the literature to make the interpretation of the wave travel time more objective. Concerning the selection of input signal, Viggiani and Atkinson [1995a] suggested the use of sine waves to reduce the degree of subjectivity of the interpretation. In fact, given their single frequency character, both the source and the received signals have the same shape, allowing the application of numerical based interpretative approaches, such as the cross-correlation technique. According to Greening and Nash [2004], allowing the application of π-point phase comparison method, if a continuous harmonic signal is adopted instead of using a single impulse, the problems caused by transient effects can be removed. Thus, in the present work, in the case of both first arrival and cross-correlation interpretation method a sine pulse wave as input signal was used, in the case of π-point phase comparison method a continuous sine wave was used.

In the following sections, the main characteristics of three interpretation approaches are discussed, namely the first arrival method, the cross-correlation and the π-point phase comparison method. All of them are based on the assumption of a plane wave front travelling through the sample and on the absence of any reflected or refracted wave, although, as said above, the real conditions during the test can be quite far from these hypotheses.

5.1. First arrival method

According to the first arrival method, the travel time $T$ can be identified directly as a time interval between characteristic points on the input and output wave signals, as shown in figure 12. This method is the most widely used procedure to interpret bender element data [e.g. Dvivik and Madshus, 1985; Viggiani and Atkinson, 1995a; Brignoli et al., 1996; Jovičić et al., 1996; Lohani et al., 1999; Perrington et al., 2001; Lee and Santamaria, 2005; Leong et al., 2005].

Point A of the input wave (Fig. 12) corresponds to the start of the transmitter motion, which is, in this case, a single sine pulse. This represents the start of the energy transfer from the source to the soil. Point A on the output wave signal corresponds to the start of the receiver motion and represents the instant of the energy transfer from the soil to the receiving bender element. It is known that the transmitter element, when excited, produces both P-waves and S-waves, so that the wave form arriving at the receiver is complex. In fact, the first energy arrival, recognized as point A on the output wave signal, is followed by an additional strong energy arrival of opposite polarity with respect to the input wave, at about the time marked as $A'$ on the output wave signal. The first arrival time of the shear wave is assumed to coincide with this deflection $A'$, because this is the arrival time of the first intense signal of proper polarity. Hereafter, the time elapsed, $T_f$, between A on the input wave and $A'$ on the output wave is the wave travel time according to the so
called “first arrival method”. The signal component of negative polarity (denoted as the A’ arrival) preceding the arrival of the shear wave is stronger when a low excitation frequency is used. This component tends to fade away as the excitation frequency increases, that is when the number of shear wavelengths between the bender elements goes from about one to four or more [BRIGNOLI et al. 1996]; SANCHEZ-SALINERO et al. [1986] and MANCUSO et al. [1989] showed that this first deflection of the receiver signal may not correspond to the arrival of the wave but to the arrival of the near-field component applying to shear wave sources of finite dimension. Near-field energy creates transverse motion having the following characteristics: propagation with the compression wave velocity, initial polarity opposite to the component propagating with $V_s$ (far-field shear wave). The near-field effect is quantified in terms of the ratio of wave path length $L_o$ to wavelength $\lambda$. $L_o/\lambda$. Its amplitude rapidly decays with increasing number of wavelengths between the source and the receiver, i.e. with increasing frequency. Both BRIGNOLI et al. [1996] and SANCHEZ-SALINERO et al. [1986] gave evidence to near-field effects masking the first arrival of the wave while ARROYO et al. [2003] showed that signal distortion is not only due to near-field effects, but also to signal distortion still occurring beyond the Stokes’ source near-field. In particular, SANCHEZ-SALINERO et al. [1986] and ARULNATHAN et al. [1998] showed that near field effects are not significant when $L_o/\lambda$ is greater than 2. More in detail, ARROYO et al. [2003] showed that if $L_o/\lambda$ is greater than 1.6 the near-field effect is less than 5%. However, JOVICIC et al. [1996] pointed out that very large frequencies ($f \geq 29$ kHz for soft-rocks) can lead to overshooting of the elements. In fact, if the input frequency is too high, the element may not respond properly, generating excessive noise in the signal. The frequency at which overshooting starts depends on the impedances of both the soil and the element and becomes a more severe problem with increasing stiffness of the soil. For the bender elements set-up and clayey material used in this work, the overshooting started at about 16-18 kHz for $p' = 700$ kPa, showing increasing frequencies for increasing stress level. Therefore, because of overshooting, there are cases in which measurements will have to be made at low frequencies, despite near-field effects.

Concerning the quality of the received signal, it is worth quoting LEE and SANTAMARINA [2005, 2006], that observe the strongest output signal when the input frequency of the single sinusoidal wave is close to the resonant frequency of the system. However, this latter resonant frequency is not constant as it depends on the resonant frequency of bender elements, as a function of the anchoring conditions and cantilever length, coupled to that of the soil, this latter being pressure and density dependent. In particular, the bender-soil system resonant frequency depends more on the bender element characteristics when the cantilever length is short ($L_o < 4$ mm), whereas it is controlled by the soil properties when the cantilever length is long ($L_o > 4$ mm). In this latter case the bender resonant frequency in air, which decreases rapidly with the cantilever length, becomes smaller than the one in soil [LEE and SANTAMARINA, 2005]. The vertical bender elements used in this work are characterised by a resonant frequency in air of about 21 kHz, the horizontal bender elements of about 12 kHz.

Alternatively to the interpretation procedure discussed above, the travel time may be taken as the time elapsed between any two corresponding characteristic points in the signals. In so doing, the near field problems should be reduced. The characteristic points that are most commonly used to identify the wave travel time are the first positive peak (point B, Fig. 12), which was also used in the present work, the first negative peak (point D, Fig. 12) [ARULNATHAN et al. 1998] and the first zero crossing (points C, Fig. 12) [LOHANI et al. 1999]. Other methods based on the visual identification were proposed in the literature [e.g. JOVICIC et al. 1996; LEE and SANTAMARINA, 2005], but are not discussed in the present work.

5.2. Cross-Correlation method

The cross-correlation method originally proposed for the analysis of cross-hole test results by MANCUSO et al. [1989], was extended to interpret bender element signals by VIGGIANI and ATKINSON [1995a] and ARULNATHAN et al. [1998]. The cross-correlation function $CC_{xy}(t)$:

$$CC_{xy}(t) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} X(T)Y(T+t) dT$$

is a measure of the degree of correlation of the two signals $X(T)$ and $Y(T)$, where $Y(T)$ is the driving signal (Fig. 13a), $X(T)$ is the signal at the receiver (Fig. 13b), $T_t$ is the total time length of the signal and $t$ is the time shift between the signals. The cross-correlation given by equation (2), is the common area subtended by the signal Y (once shifted in time by $t$) and the signal X. For an impulse wave that has been recorded at two space points, the $CC_{xy}$ will reach a maximum value ($CC_{xy_{max}}$) for the time shift $t$ that equals the travel time of the impulse between the two points. This time shift may be taken as the travel time of an impulse wave between the two benders; generally the time shift used is that referring to the wave peaks, $T_{CC}$, as shown in figure 13c. The cross-correlation technique requires the time domain record to be decomposed into a group of harmonic
waves of known frequency and amplitude; a convenient algorithm for this purpose is the Fast Fourier Transform (FFT).

Figure 13c shows the cross-correlation of the signals reported in figure 13a, b normalized with respect to the maximum absolute value, \( CC_{\text{norm}} \). According to the results presented by Viggiani and Atkinson [1995a] for the \( V_{\text{vh}} \) measurements, the travel time defined by the cross-correlation \( (T_{\text{CC}}) \) is always significantly larger than \( T_F \), corresponding to the first deflection of the received signal, up to 50% difference between \( T_{\text{CC}} \) and \( T_F \). In the case reported in figure 13, instead, the travel times defined by means of the first arrival method and the cross-correlation method are very similar. This is due to the fact that, in this case, the input and output signals are characterised by similar ranges of frequencies, as shown by the linear spectra of the two signals reported in figure 14. The input signal \( (Y(T), \text{Fig. 14a}) \) is characterised by a frequency of 4 kHz and the output signal \( (X(T), \text{Fig. 14b}) \) by 3.9 kHz. In fact, according to Santamarina and Fam [1997], the determination of the travel time using the cross-correlation method is only valid if both input and output signals are of the same “nature” and, according to Jovicic and Coop [1997], if the shape of the input and output wave remains unchanged. However, these two conditions are very difficult to be achieved during bender element testing due to the wave interferences with the specimen boundaries, the signal distortion and the near-field effects [Arul Nathan et al., 1998].

5.3. \( \pi \)-point phase comparison method

The “\( \pi \)-point phase comparison method” was proposed by Kaarsberg [1975] and reviewed by Greening and Nash [2004]. The latter authors tested it during bender elements bench tests performed on reconstituted Gault clay specimens of about 190 mm height and 100 mm diameter. This frequency-domain method uses a continuous sine wave input and produces a continuous sine wave output. The approach used in the method is based on the assumption that the frequencies of both the input and output signals are identical and that the output wave starts with a time delay (or phase angle) which depends on both the wave frequency and the distance between the bender elements. This method requires the detection of the relationship between phase and frequency of the input and output signals to be performed, based on the scheme described below.

If a set-up with bender elements separated by a tip-to-tip distance \( L_0 \) is considered and the bender
elements are excited by a continuous sinusoidal voltage of amplitude $A$ and harmonic frequency $f$, the input and output signals are given by:

$$y_{in} = A \sin(\omega t)$$

$$y_{out} = B \sin(\omega t - KL_n)$$

where $A$ is the amplitude of the input signal, $t$ is the elapsed time, $B$ is the amplitude of the output signal, and $\phi = KL_n$ is phase angle, $K = 2\pi\lambda$ is the wave-number and $\lambda = V_s/f$ is the wavelength, $V_s$ being the shear wave velocity, while $\omega = 2\pi f$ is the angular frequency, this latter being assumed as being the same for both input and output signals.

The phase angle, the shear wavelength $\lambda$ and the tip-to-tip distance are related as follows:

$$\phi = KL_n = 2\pi \frac{L_n}{\lambda}$$

The transmitted and received signals are fed into the oscilloscope, which has a time-independent display showing the input wave versus the output wave. The resulting Lissajous plot gives an indication of whether the two signals are in or out of phase with respect to each other. When the phase angle is an odd multiple of $\pi$ (e.g. $\pi, 3\pi, 5\pi$, etc.), a plot on the oscilloscope produces a straight line tilting to the right and the signals are out of phase (Fig. 15). For even multiples of $\pi$, the plot produces a straight line tilting to the left and the signals are in phase (Fig. 15).

The procedure consists of sweeping a range of frequencies (usually from 1 to 20 kHz) and recording successively the frequencies at which the signals become in or out of phase. Ideally, a list of increasing frequency values will be produced, each value having associated phase angles that increase by $\pi$. An increase of $\pi$ for the phase angle represents an increase of 0.5 of the $L_n/\lambda$ ratio. Finally, a plot of frequency against $L_n/\lambda$ is obtained and, according to the model:

$$\frac{L_n}{\lambda} = \frac{fT}{2\pi}$$

The plot should represent a straight line crossing the origin, with a gradient equal to $1/T$, where $T$ is the time that the shear wave emitted by one bender element takes to travel from the transmitter, through the material, to the receiver element. BLEWETT et al. [2000] showed that the relationship often contains non-linearities, related to dispersion phenomena due to the test set-up. The nonlinear behaviour may arise anywhere between the transmitter and receiver elements. These phenomena can occur for a number of reasons, such as: the effect of specimen boundaries, the frequency dependence of the material constitutive parameters, the wave scattering due to material non-homogeneities, the dissipation of the wave energy into heat and, finally, the amplitude dependence of wave velocity [e.g. ARROYO et al., 2001; 2003]. GREENING and NASH [2004] found that it is practically impossible to assess the phase relationship by the $\pi$-point phase comparison method for a relatively low frequency range (0-3 kHz), because of the noise that dominates the signal, whereas for larger frequencies (3-10 kHz) a more steady value of travel time can be identified. The authors also detected some anomalies in the data observed during $V_{vh}$ measurements, which were not detected in $V_{hv}$ measurements; therefore they interpreted this as a geometry-related effect.

No unique straight line could be identified from the analyses of the results proposed in this paper; on
the contrary, two or three different trend lines were deduced, each suggesting a different travel time (Fig. 16). As shown in figure 16a, b, c, for measurements carried out during the $\eta = 0$ test at $p' = 175$ kPa, the travel times found with the $\pi$-method $T_\pi$ for VH, HV and HH signals, were very different from the travel times identified by means of the first arrival method $T_F$ despite the use of a relatively high frequency. As mentioned above, this inconsistency should be related to the dispersive behaviour that may arise anywhere between generation of the input signal and the final measurements point [BLEWETT et al., 2000].

It is worth noting that when using the first arrival method to interpret the results of bender element tests carried out at high pressure after isotropic compression of reconstituted Lucera clay, similar arrival times for the HH and HV waves were deduced, as expected for an isotropic material. This was not the case when the same data were interpreted by means of the $\pi$-point phase comparison method, which leads to rather different, and unreal-
istic, travel times. Therefore, the discussion above strongly suggests that the $\pi$-point phase comparison method did not perform well with the data logged in the present study on Lucera clay.

5.4. Comparison of the results from the different methods

The input signals employed in all the tests were single sinusoidal pulses of different frequencies, when using first arrival and cross-correlation method, while they were continuous sinusoid when using the $\pi$-point phase comparison method. The amplitude of the input signals in the three cases was fixed at $\pm 10$ V. The tip-to-tip distances ($L_a$) between the transducers were used to calculate the shear wave velocity of the samples. All the test traces were first examined in the time domain to obtain the travel time according to the first arrival method, then the cross-correlation and $\pi$-point phase comparison methods were employed for comparison. In the following, the arrival time located at the first “significant” deviation from zero, (time interval between input point A and output point A’ in Fig. 12), is identified as $T_f$ and called “first arrival time”. The travel time defined as the interval between two characteristic points, i.e. peak-to-peak (“interval B-B” in Fig. 12), is identified as $T_{pp}$. The travel time derived from the cross-correlation method is identified as $T_{cc}$ and the time defined by means of the $\pi$-point phase comparison method, is defined as $T_{\pi}$.

As an example, figure 17 shows the determination of the travel time by means of the three different methods for the $V_{hh}$ wave during the bender element test performed at $p' = 350$ kPa and $q = 105$ kPa in test 2 ($\eta = 0.3$). In this case, the $\pi$-point phase comparison method (Fig. 17a) results into three different trend lines for $0.5 < L_a/\lambda < 4$, each one corresponding to a different travel time. This observation is in agreement with SANCHEZ-SALINERO et al. [1986], ARULNATHAN et al. [1998], PENNINGTON et al. [2001], ARROYO et al. [2003], LEONG et al. [2005; 2009], which highlighted the role of the ratio $L_a/\lambda$ on the arrival time. Accord-
According to Leong et al. [2005], more reliable estimates of the S-wave velocity should correspond to $L_a/\lambda=3.33$: in fact, as shown in figure 17, for $3.5<L_a/\lambda<4$ the travel time $T_\pi=0.000144$ s is closer to the travel times detected by means of the first arrival method, although it keeps being larger than those latter.

A special remark should be made on the cross-correlation method (Fig. 17b) for which, in this case, it is not possible to recognise a single peak, as the analysis of the data leads to an output signal (Fig. 17b) characterised by at least three significant peaks. According to the cross-correlation theory, the maximum positive peak, denoted as $2$ in figure 17b, provides a travel time equal to $0.00016$ s, while the first arrival identification gives a value of $T_F = 0.000106$ s (Fig. 17c). The latter is very similar to the value ($T_{pp}=0.000104$ s) of the interval peak-to-peak in figure 17c.

It is evident that, in the case discussed above, the three methods provide rather different travel times. This observation can be generalised, as a similar pattern in the comparative analysis between the different interpretation methods was observed for most of the bender element tests discussed in this paper.

Figure 18 summarises the evolution of the shear stiffness moduli $G_{vh}$ (Fig. 18a), $G_{hv}$ (Fig. 18b) and $G_{hh}$ (Fig. 18c) during test 4 (Fig. 10) based on the travel time deduced by means of the first arrival and the cross-correlation methods. In this comparison, the $\pi$-point phase comparison method was not considered because it was not possible to select a single travel time for each bender element test, i.e. for each stress state being investigated. For both $G_{vh}$ (Fig. 18a) and $G_{hh}$ (Fig. 18c) the travel time deduced by means of the cross-correlation ($T_{CC}$) was always significantly larger than $T_F$, corresponding to the first deflection, the discrepancy being of about 50%. Nonetheless, the stiffness data derived according to both the first arrival and the cross-correlation methods follow parallel straight lines in the log $G_{ij}$ – log $p'$ plot, of the same gradient $\approx 0.82$, irrespective of the adopted interpretation method. For the $G_{hv}$ (Fig. 18b) moduli, those deduced by means of the cross-correlation method appear to be more scattered than those deduced by the first arrival method, the discrepancy between the two interpretation results achieving a maximum percentage of about 80%. It is worth observing that in this case the moduli calculated by means of the first arrival

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**Fig. 18** Comparison between cross-correlation method and first arrival method during test 4 ($\eta=0.8-0.1$): a) $G_{vh}$; b) $G_{hv}$; c) $G_{hh}$.

**Fig. 18 – Confronto tra la cross correlation e il first arrival per la definizione dei moduli di rigidezza a taglio durante la prova 4 ($\eta=0.8-0.1$): a) $G_{vh}$; b) $G_{hv}$; c) $G_{hh}$.**
method lie on a straight line of the same gradient (≈ 0.82) as those regressing the \(G_{th} - p'\) and \(G_{nh} - p'\) data. The observed differences between the \(G_{ij}\) values obtained by the first arrival and the cross-correlation methods, shown in figure 18 for test 3, are numerically consistent to the corresponding ones observed in all the other tests performed in this study.

Figure 19 highlights the influence of the frequency of the input signal on the stiffness values deduced by means of the first arrival and cross-correlation methods. In the case of the first arrival method, the travel time is deduced accounting for both the interval between the input wave start and the first deflection point of the output wave (A-A’ in Fig. 12) and the interval between the positive input wave peak and the first positive output wave peak (B-B in Fig. 12). In particular, the figure refers to two different stress states during tests 3, \(p' = 700\) kPa and \(q = 420\) kPa, and 5, \(p' = 70\) kPa and \(q = 56\) kPa. The data show that the input signal frequency does not affect significantly the stiffness values obtained by the use of the first deflection characteristic point, whereas it does affect the values obtained using either the peak-to-peak time or cross-correlation method. This latter method is seen to result in significant overestimation of stiffness \(G_{th}\), in test 5 (Fig. 19b). In test 3, instead, in \(G_{nh}\) measurements corresponding to input and output waves of very similar frequencies, \(T_{CC}\) and \(T_F\) happen to be very close.

Observations of the type discussed above have been recorded all way through the work proposed in this paper and, as such, have confirmed that the first arrival method based on the first deflection may be considered the most robust to interpret the bender element signals, as already pointed out by other researchers [e.g. LEONG et al., 2009], despite the well known degree of subjectivity inherent to this interpretation method. However, it should be considered that this subjectivity reduces with increasing experience. As such, this method has been selected as the most appropriate to evaluate the velocities and the relating shear moduli discussed in the following section.

6. Evolution of \(G_{hh}\) and \(G_{hv}\) according to the first arrival method

In figure 20a, the values of the small-strain shear moduli \(G_{hv}, G_{vh}\) and \(G_{hh}\), as deduced applying the first arrival method to the interpretation of the bender element data from test 3, characterised by \(\eta = 0.6\), are plotted against \(p'\) in a logarithmic scale. Figure 20b plots the shear modulus \(G_{ij}\), on a logarithmic scale, against specific volume \(v\). The variation trend of \(G_{ij}\) with \(p'\) and \(v\) shown in the figure is representative of those observed in all the tests of figure 10, irrespective of the stress ratio being imposed. All \(G_{ij}\) values increase with increasing mean effective stress and decreasing specific volume and, for a given mean effective stress, they increase with increasing overconsolidation ratio. In addition, the figure shows that the \(G_{hh}\) values are always slightly higher than the \(G_{hv}\) and \(G_{vh}\) values and that the \(G_{hh}\) measurements lie on a best-fit line nearly parallel to that relative to the \(G_{hv}\) and \(G_{vh}\) measurements, in both the \(G_{ij} - p'\) and the \(G_{ij} - v\) plots. As shown in figure 20a,b the \(G_{hv}\) and \(G_{vh}\) measurements are quite similar during test 3, and the ratio \(G_{vh}/G_{hv}\) varies between 0.98 and 1.05. In the case of test 4 (Fig. 18), for example, using the travel time defined by means of the first arrival method (\(T_F\)), this ratio varies between 0.94 and 1.1. Those ranges of ratio variation are quite similar to what observed for reconstituted Gault clay by PENNINGTON et al. [2001]. As suggested by these Authors, the difference between \(G_{hv}\) and \(G_{hh}\) is probably related to the different set-up of the vertical and horizontal bender elements. If the cross-correlation method is adopted to interpret the same data set, the corresponding ratio \(G_{vh}/G_{hv}\) varies between 1.3 and 3, attaining unacceptable values and, as such, confirming its unsuitability to analyse bender elements experimental data.

For stress cases characterised by \(p'\) lower than 175 kPa, the \(G_{ij}\) values measured in the different tests (Fig. 10) are very similar. The test results relative to normally consolidated states for \(p' = 100\) kPa is the reference pressure. In this pressure range, the \(G_{ij}\) values are influenced by the different imposed constant-\(\eta\) compression path. According to PENNINGTON et al. [2001], comparing the measurements of \(G_{nv}\) with \(G_{nhv}\), instead of \(G_{nh}\), has been considered preferable because both \(G_{nv}\) with \(G_{nhv}\) were recorded using the horizontal bender elements, thus according to the same benders set up. It can be observed that \(G_{hh}\) is always larger than \(G_{nv}\) and that both the \(G_{nh} - p'\) and the \(G_{nh} - p'\) data follow straight lines in each single constant-\(\eta\) compression test. These lines have the same gradient, but they have different intercepts, varying with \(\eta\). Figure 21 shows that the differences in the intercept values are larger for the horizontal stiffnesses than for the vertical ones, i.e. the horizontal stiffness is more influenced by the radial compression stress ratio than the vertical stiffness.

Therefore, the relationship:
proposed by Rampello et al. [1997] for the variation of the vertical stiffness \( G_{bh} \) of normally consolidated clays with the mean effective stress appears to be valid also for the stiffness measured in the horizontal direction. In addition, the increase of \( G_{vh}^{(NC)} \) with \( p' \) is controlled by a single exponent \( n \approx 0.81 \), for all the compression paths, either isotropic or anisotropic (Fig. 21a,b). The \( n \) value found in this investigation is located in the upper portion of the range of \( n \) values proposed by Vigliani and Atkinson [1995b] for the \( G_{vh} \)-\( p' \) relation, given the plasticity index of Lucera clay. Increasing values of \( S_\eta \), which represents the value of \( G_{vh}^{(NC)} \) at the reference stress \( p' = p_r \), are obtained for increasing values of \( \eta \).

For test 4, the change of stress ratio at \( p' = 700 \) kPa, going from \( \eta = 0.8 \) to \( \eta = 0.1 \) (Fig. 10), does not
seems to influence significantly the pattern of variation of $G_{ij}$ with increasing $p'$ (Fig. 21). For test 5, the change of stress ratio at $p'=550$ kPa, from $\eta=0.8$ to $\eta=0.1$ (Fig. 10), does not seem to influence the $G_{ij}$ trend up to $p'=700$ kPa. Thereafter, the stiffness data move towards the $G_{ij}$-$p'$ curve found for isotropic compression (Fig. 21).

**Conclusions**

The results of this study, in line with the literature concerning the methods of interpretation of bender element test results, show that, for bender element tests performed in a triaxial system on reconstituted Lucera clay, the first arrival method is the most robust...
and appropriate method to identify the travel time of shear waves propagating either vertically or horizontally in the sample. It provides more consistent results for both vertical and horizontal directions, as compared to the cross-correlation and \( \pi \)-point phase methods. In particular, for Lucera clay, the \( \pi \)-point phase comparison method gives rise to erroneous results, probably due to the low input frequencies adopted in the tests and to the effects of the boundary conditions of the specimens, of cylindrical shape (76 mm height and 38 mm diameter). The travel time deduced by the use of the cross-correlation approach was always significantly larger than the one deduced using the first arrival method. In certain experimental circumstances, as for example in the measurements of \( G_{hv} \), the cross-correlation method led to far more scattered results, probably due to the relative stiffness of the soil and the bender, to the degree of fixity of the bender element into the brass cylinder probe and also due to larger differences between the frequencies of the input and output signals.

With reference to the mechanical behaviour of the reconstituted soil under study, the results presented in the paper, when the bender element data were interpreted by first arrival method, have demonstrated that the single line both for \( G_{hv} \), as already found by Rampello et al. [1997], and for \( G_{hh} \) can be fitted by equation (7). The results show that the index “n” is the same for \( G_{hv} \) and \( G_{hh} \), irrespective of both the stress ratio \( \eta \) and the direction of propagation of the shear wave. In particular, Lucera clay is characterised by \( n=0.81 \). Furthermore, the imposition of a new stress direction tend to change the stiffness path and to induce a new one, consistent with the new stress condition. In fact, when the virgin compression stress ratio changes, the pattern of variation of the stiffness components \( G_{hh} \) and \( G_{hv} \) also changes with \( p' \), since it tends towards that consistent with the new stress ratio conditions.

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Misure multidirezionali con bender elements in cella triassiale: realizzazione dell’apparecchiatura e interpretazione dei segnali

**Sommario**

L’articolo illustra, dopo una dettagliata descrizione delle fasi di costruzione di bender elements verticali e orizzontali e della loro implementazione in apparecchi triassiali a percorso di carico controllato, il confronto tra i tre metodi più utilizzati di interpretazione dei segnali dei bender elements per definire il tempo di arrivo dell’onda di input al bender ricevitore. I tre metodi sono: il metodo che si basa sull’analisi visiva delle caratteristiche dell’onda di output, il metodo della cross-correlazione e il $\pi$-method. Sulla base delle misure eseguite con i bender elements durante il lavoro di ricerca qui presentato si è dedotto che, per il materiale testato e per le condizioni al contorno durante le prove, il miglior metodo per identificare il tempo di arrivo dell’onda di input al ricevitore è quello basato sull’analisi visiva delle caratteristiche delle onde di output. La strumentazione descritta è stata approntata per poter studiare l’evoluzione dei moduli di rigidità a taglio $G_{ij}$ lungo percorsi di carico isotropi e anisotropi ognuno presso elevati nelle sole dell’argilla ricostituita di Lucera (Sud Italia). Si è osservato che le deformazioni plastiche sviluppatisi nel materiale a seguito dei percorsi di carico applicati tendono a modificare l’iniziale percorso dei moduli $G_{ij}$.  


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